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Soil factors affecting the growth of quaking aspen forests in the Lake States

Joseph Henry Stoeckeler

oil Factors Affecting the Growth of Quaking Aspen Forests in the Lake States

Joseph H. Stoeckeler[1]

STUDY[2] reported here was made for the purpose of relat-[illegible] growth rate of quaking aspen in the Lake States to the physical and chemical properties of the soils. The effect of shallow water tables and the role of repeat burns were also studied.

Foresters, as well as agronomists and those engaged in soils research, are interested in appraising the productivity of different classes of soils, since this is important in terms of land-use planning, land-purchase prices, and management plans.

The forester deals with a long-range crop measured in terms of cords, cubic feet, or board feet, and relates yields to slope, exposure, altitude, soil type, soil-profile characters, soil texture, permeability or friability of soil, general soil-moisture relations, or comparative abundance of organic matter. Often as many as four to six site factors may be meaningful in terms of wood production of a given species of tree, and two or three are likely to be of paramount importance.

The productivity of a specific soil or set of conditions, as it affects tree growth, is very easily determined if the site is occupied by a stand of trees of sufficient age and density so that direct measurements can be made of the diameters and merchantable heights or total heights of trees on a sample unit of area. These are recorded on a one-fifth or one-tenth acre plot; this information is converted to a per-acre basis, and then to a per-acre, per-year basis in terms of several volume criteria already mentioned. By looking these yields up in appropriate tables or by reference to yield curves based on age, the forester can then classify the site into one of five site or productivity classes.

An even simpler method involves use of site index. Site index is an expression of the height of the average dominant and codominant tree as predicted at a certain age of a specific species of tree. It is applicable only to stands that are comparatively even-aged. Relation-

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ships have been established showing that the yield of a stand in terms of solid wood content is very closely related to site index, with correlation coefficients as high as $r = .923$. For site-index determination, all that is necessary is to measure the height of about 5 to 10 trees appropriately selected within the dominant and codominant tree classes; determine average total age of several trees by use of an increment borer, which removes a core of wood about 0.2 inches in diameter on which the annual rings are counted; and look up on a site-index curve the site class of the specific plot. Both the direct volume measurement and the site index of productivity have some weaknesses. The former cannot be applied until there is a considerable volume of timber present over 5 inches in diameter. Site-index evaluation in aspen is not particularly accurate until trees are at least 20 years old or 25 to 30 feet high. These methods are also inapplicable on land devoid of trees due to logging, land clearing, or forest fires, since there is nothing to measure. Size of stumps might on occasion yield a clue as to the soil productivity for tree growth.

One alternative in the situations stated is to classify the site by soil and other characteristics and compare these with data obtained on sites where trees large enough to measure for site index are present.

A second alternative is to study the ground vegetation on the site to be determined and compare it with that found on sites where the trees are present and where the site index could be determined.

The ground vegetation approach, using "indicator" plants as a key to the relative soil productivity, has a weakness in that some barren or denuded sites, recently logged areas, burns, or old fields recently abandoned for agricultural use may not have typical vegetation found under well-developed forest stands.

In the present study, site index was used as the primary index of productivity of soil on which the aspen stands were growing.

Review of Literature

LIFE HISTORY, CHARACTERISTICS, AND ECONOMIC IMPORTANCE OF ASPEN

QUAKING ASPEN (*Populus tremuloides Michx.*) is the most widely distributed broadleaf tree species found on the North American continent. It is found from the New England states and the Appalachian Mountains as far west as the Sierra Nevada Mountains of California; as far south as Illinois, Kentucky, and Missouri; and as far north as Alaska to Laborador.

Aspen is a rather short-lived tree, attaining an age at maturity of 50 to 70 (occasionally 80) years in the Lake States region of Minnesota, Wisconsin, and Michigan (Kittredge and Gevorkiantz, 1929). In the Rocky Mountain region it may attain ages up to 125 to 130 years (Baker, 1918). The maximum diameter at breast height and total height are 20-24 inches and 80 feet, respectively, in the Lake States. Often it reaches only 12-14 inches in diameter in the Lake States (figure 1) after which it succumbs to heart rot (Schmitz

Fig. 1. A 50-year-old stand of quaking aspen in northern Minnesota.

and Jackson, 1927; Johnson *et al.*, 1930; Zon, 1928). Hypoxylon canker contributes to early breakup of some stands (Christensen *et al.*, 1951). Clonal variation may account for as much as 7 to 10 feet difference in site index on apparently identical soils.

The aspen sets seed in May or early June (Zehngraff, 1947; Sinev, 1940) and is capable of producing enormous amounts of seed. Sinev (1940) states that in Europe it may produce from 400 to 500 million seeds per hectare (2.47 acres) in a good seed year with a germination of 90 percent when collected.

The seed is comparatively short-lived (Moss, 1938) and prefers bare mineral soil as a seedbed, particularly as found in burns caused by forest fires. Sinev (1940) found 2.9 seedlings per square meter, i.e., the maximum number of seedling aspen, when the forest soil was burned and scarified, 1.0 when burned and not scarified, 0.22 when untreated.

It also reproduces abundantly by suckers which develop from dormant buds on roots near the surface in the presence of strong light (Barth, 1942) or new buds formed in the season of sprouting (Sandberg and Schneider, 1953). Aspen suckers for at least two years after cutting (Baker, 1918). It suckers most abundantly in well-aerated soils (Weigle and Frothingham, 1911). Seedlings are rated superior to suckers in shade tolerance (Weigle and Frothingham, 1911).

In Europe, Barth (1942) reported aspen originating from seed has better form, thinner branches, and better height growth and is less susceptible to rot than are trees of sucker origin.

Reim (1929) found that aspen in Estonia and Finland will flower as early as 8 to 10 years of age, and that the seed will spread readily to distances of 400 to 500 meters (1,312 to 1,640 feet).

The propensity of aspen stands to sucker profusely upon logging (which admits an abundance of light), or upon being burned, keeps the species perpetuated. Its wide-spreading root system aids it in extending the ground it occupies. Day (1944) found a main lateral root 47 feet long on an 18-year-old aspen which was 25 feet high. It had vertical sinker roots to a depth of 7.5 feet. This single root had eight suckers on it, and many more on its branch roots. One 8-year-old aspen seedling had a lateral root 30 feet long. A considerable area of the aspen type, perhaps 10 million acres, is of rather poor quality and might profitably be eventually converted to other forest types by planting pine or spruce (Shirley, 1941). In a revised estimate of this figure, Chase (1947) sets the acreage of poor site at 6.2 million acres.

In spite of its attainment of only rather small diameters (Telford and Malcolm, 1947) and some defects in technical properties (Johnson, 1947)—such as low compression strength and some tendency to warp in drying or if cut in lengths more than 8 or 10 feet long—aspen is used rather extensively for lumber for box boards, crating, core stock, and toys (Zasada, 1947). The yields of good grades of lumber are rather low, on occasion no more than 14 percent of number 1 common or better (Zasada, 1948). Some of the better grades are used for paneling.

Many of the larger diameter stands have been heavily cut over in the last 20 years and now about 50 percent of all the aspen in the Lake States is in the seedling and sapling stage (Zasada, 1950).

Aspen occupies 19.8 million acres of commercial forest land of the three Lake States, or 39 percent of the total forest acreage. It far exceeds the northern hardwood type, which is second with 19 percent (Chase, 1947). In Minnesota alone, it occupies 45 percent of the commercial forest area of the state. It occupies 7.5 million acres, on which there are 1,850 million cubic feet of wood, or 24.6 million cords of wood (4′ x 4′ x 8′). In this state, about 1.5 million acres of aspen are on good site, 4.1 million on medium site, and 1.9 million on poor site (Chase, 1947).

The chief commercial use of the aspen harvested in the Lake States is pulpwood. It is now the leading species for pulpwood in this region. In 1950, aspen accounted for 694,000 cords out of a total of 1,873,000 cords cut in the Lake States, i.e., over one-third. Minnesota supplied 248,000 cords of this aspen (Horn, 1950). It is suitable only for the lower grades of paper, being rather short-fibered (Schafer, 1947), but can be used in better grades if mixed with about 50 percent of longer fibered species such as spruce or balsam fir.

SITE INDEX AND GROWTH

In relating site index to growth of trees, one of the principal criteria has been texture (Haig, 1929; Wiedemann, 1934; Roe, 1935; Kittredge, 1938; Stoeckeler, 1948; Youngberg and Scholz, 1949; Hills, 1952; Coile, 1952). With most tree species the soils of higher silt-and-clay content were associated with better site and higher productivity, at least in the texture range of sands through silt loams. A few investigators found reverse trends of texture and site index (Gaiser and Merz, 1953; Shipman and Rudolph, 1954). Westveld (1952) found a relationship of forest types to soil map types. Tarrant (1949) found no relation of Douglas-fir growth to soil properties.

Good aeration of the soil and satisfactory internal drainage are necessary for good growth (Diebold, 1935; Turner, 1937; Wallihan, 1949; Hartmann, 1951; Pierce, 1953). The depth to mottling has served as an indicator of internal drainage and aeration (Ralston, 1951; Coile, 1952; Aird and Stone, 1955).

The thickness of the total A horizon or of the A_1, has been correlated with site index (Auten, 1937a; Auten, 1937b; Lutz and Chandler, 1946; Gaiser and Merz, 1953; Young, 1954). Better sites were associated with greater thickness of the A or A_1 horizons. Humus type may likewise have an effect on productivity, with mulls favored over mor (Romell, 1935; Heiberg, 1941).

Soil depth, or distance from the soil surface to bedrock, has been found to be a factor of significance in tree growth—the shallow soils having the poorer growth rates (Westveld, 1933; Storie and Weislander, 1948; Gessel, 1949).

Soils with a high stone or gravel content had poorer growth than those with a minor amount of rock (Locke, 1941; Viro, 1947; Carmean, 1954).

Although some pioneer species have a modest requirement for nutrients (Kellogg, 1934), soil nutrient level has been determined to affect productivity of the site, with the better soils producing more growth (Nemec and Kvapil, 1926; Hickock *et al.*, 1931; Alway and McMiller, 1933; Lunt, 1939; Wilde *et al.*, 1949; Aaltonen, 1950b; Wilde and Paul, 1951). Extremely acid soils, often associated with poor soil nutrient status, tend towards low productivity (Youngberg and Scholz, 1949; Schönhar, 1954).

Besides the soil factors, precipitation, or its effectiveness, has been useful in explaining differences in productivity (Hill *et al.*, 1948; Gessel, 1949; Von Hackmann, 1954) with the areas of higher rainfall or rainfall effectiveness showing the greatest growth potential.

In rolling or mountainous country, topographical features, slope, and exposure have a prominent role in productivity. The hot, dry, southwest exposures tend to show substantially less growth rate than the cooler north and northeast slopes (Arend and Julander, 1948; Gaiser, 1951; Gysel and Arend, 1953) and ridge tops are less favorable sites than lower slopes or coves (Arend and Julander, 1948). Areas of high elevation with their shorter growing season and cooler climate have shown poorer growth than those of lower elevation (Carmean, 1954).

A few investigators have related site to ground vegetation (Ilvessalo, 1933; Aaltonen, 1950a; Westveld, 1954). Hansen (1946) found a better correlation of jack-pine growth with other indicator species than with soil texture or nutrients.

FOREST FLOOR AND LEAF ANALYSIS

Voigt *et al.* (1957) found some positive relationships of foliar analysis and site index in quaking aspen in northern Minnesota, while Daubenmire (1953), working with some Rocky Mountain species, found no relationship.

Foliar analyses have a weakness; to keep data comparable, sampling must be done almost simultaneously or at least in a limited span of time. A number of investigators have demonstrated considerable variation in nutrient content of foliage with season of sampling (Olsen, 1948; Aaltonen, 1950a; Maki, 1951; Owen, 1954). White (1954) found that the place of sampling in the crown had a measurable effect on the foliar analysis. Lunt (1947) found extreme variability in nutrients in petioles of clones of the same genus of poplars, thus adding still another variable to the problem.

It is apparent that a great deal more research is needed before foliar analysis for forest trees is usable as a criterion of site or is as useful an indicator of nutrient status as it is, for instance, in the highly developed citrus industry (McCollam and Fullmer, 1954).

FOREST FIRE EFFECTS ON SITE AND TREE GROWTH

The role of forest fires in affecting site index of trees on a specific soil or group of soils is yet not clearly understood. In the Lake States, Alway and

Rost (1928) came to the conclusion that forest fires were detrimental to the soil in regard to the overall nutrient balance, especially in loss of organic matter, ranging from 7 to 26 tons per acre, and nitrogen, ranging from 450 to 1,500 pounds per acre.

A subsequent study in quaking aspen (Stoeckeler, 1948) indicated that repeat burns in existing aspen stands reduced potential site index by as much as 10 to 15 feet, or even more on very sandy soils. Fire scarring of the trunks and damage to root systems were cited as part of the reason for the adverse effect of fires.

In other regions studies have cited the adverse effect of intense or repeat burns on organic matter (Rowe, 1953; Austin and Baisinger, 1955).

In two studies, no adverse effect of burns was noted as regards nitrogen content of the soil (Heyward and Barnette, 1934; Ferrell and Olson, 1952).

It is probable that the effect of fires is influenced by the tree species and its nutrient needs, its sensitivity or resistance to damage by fire, the type and amount of organic debris and litter present, weather and fuel conditions, and the intensity and completeness of burn.

CORRELATION OF PRODUCTIVITY, SOIL, AND OTHER FACTORS AS OBSERVED IN OTHER FIELDS

Foresters can profitably study experiences in crop responses in agriculture to obtain leads on factors that might be meaningful in terms of tree growth, and their statistical and graphical means of handling the data.

Bray (1948), in discussing correlation of crop responses to fertilizer additions, proposes a theoretical concept for a case where two diffent nutrient elements are inadequate. He suggests that yield, expressed percentage-wise, will be the product of the sufficiency of A times sufficiency of B. He suggests the concept may work for available potash, phosphorus, and magnesium. As regards nitrogen, he suggests plant-tissue tests are probably the solution to control. He believes the "yield" concept would not apply to nitrate nitrogen and water; he doubts whether general correlations can be found between exchangeable calcium and yield in a "normal" carbonate-free soil. Bray's yield concept, as a product of sufficiency of several specific nutrients, might apply to growth or yield in certain forest species as long as the unit of yield was in terms of cords, board feet, or cubic feet, but it is almost a foregone conclusion that it would not apply to site index. The first three are volumetric expressions based on three dimensions. The last (site index) is a one-dimensional expression based on height of the average dominant and codominant tree in feet, and a product-of-sufficiency approach to the nutrient problem would no doubt produce excessive penalties against even moderate deficiencies of P, K, Mg, or Ca.

Smith and Cook (1953) have obtained high correlation of percentage of full yield of wheat and available phosphorus as determined by the Bray absorbed phosphorus method, using a 1:50 extracting ratio. Correlation coefficients (r) ranged from .454 for Spurway reserve P test, .534 for Spurway's test for active P, to .660 for the Bray absorbed P test. Ulrich (1948) has elaborated Bray's concept. He refers to a critical zone as a separating line between zones of luxury consumption and poverty adjustment. Foliar analysis is cited as a means of detecting the relative nutritional status of certain plants, especially in orange, cherry, and apple.

Close correlations of specific soil tests with each other are apparently much easier to establish than is the case of crop yield and soil tests. At least the former appear to yield considerably higher correlation coefficients. Chandler

(1939) shows a very close correlation between exchange capacity plotted over loss on ignition, the former being about twice the latter when both are expressed as percents. Lunt (1932) showed good correlation of volume-weight and percent of organic matter. Coile (1952) demonstrated the well-known correlation of percent of silt-plus-clay and moisture equivalent.

Kellogg (1930) found there is a close correlation of base exchange capacity of specific horizons (A_2 and B_2) with the percent of clay in a soil in the Miami series.

Hooghoudt (1952), in working with problems of drainage in the Netherlands, presents some relationships of crop yield and water tables that have a direct parallel in forest-growth relations in Lake States forests and should be of great interest to foresters investigating site. Hooghoudt states that the water table in much of the Netherlands is at a depth of about one-half meter in winter, and between one and one and one-half meters in summer. When yield of potatoes expressed in hundredweights is plotted over depth to ground water in inches, a rather symmetrical paraboloid curve is obtained, with values as follows in terms of hundredweight and depth respectively: 120 hundredweight at 25 inches, 180 hundredweight (the peak yield) at 50 inches, and 120 hundredweight at 75 inches. He also shows that excessive oscillation or change in water-table level adversely affects yield, as a straight-line relationship, with a yield of 180 hundredweight at a 25-inch fluctuation, and only 140 hundredweight at a 60-inch fluctuation in water table.

Both of Hooghoudt's observations on depth of water table and its total or extremes of fluctuation during the season have a direct bearing on Lake States forests, although the optimum average depth of water table for deeper-rooted tree species might be slightly deeper than the 50 inches found for potatoes in the Netherlands.

IMPROVEMENT IN GROWTH OF ONE TREE SPECIES BY MIXTURE WITH OTHERS

General observations in Europe have indicated that under certain conditions, and with spruce particularly, a monoculture cropping method repeated for a number of generations may cause some reduction of the full growth-potential due to adverse effect on soils; it may increase the tendency of some species to form raw humus, or cause excessive acidity, or cause excessive shading of the soil.

Conversely, keeping some broadleaf species such as beech or birch mixed with the conifers, notably spruce, tends to improve growth conditions because of the tendency of the hardwoods to form a more base-enriched and less acid forest litter than the spruce do (Hesselman, 1925).

Aaltonen (1950a) found aspen, birch, maple, and ash to be superior to the conifers in Finland in base and nitrogen content of the foliage.

Cline (1949) and Potzger and Friesner (1937) point out the tendency of hemlock to be especially acidic. The former noted leached layers as much as ⅛- to ¼-inch thick found under single trees (presumably old) of hemlock. The leached layer was assumed to have been formed in the lifetime of that specific tree. The latter investigators found surface pH in hemlock mostly in the range of 4.5 to 5.0 while it was in the range of 5.5 to 7.0 in deciduous forest.

Kittredge (1948) reported that a number of tree species including black locust are capable of fixing atmospheric nitrogen, and McIntyre and Jeffries (1932) noted a marked improvement in growth of catalpa where it was grown in association with the nitrogen-fixing black locust. Young (1929) found a similar situation where black locust benefited boxelder.

Experimental Procedures

ONE HUNDRED FOUR PLOTS of quaking aspen (*Populus tremuloides Michx.*) were selected for study, of which 78 were located in northern and north central Minnesota and 26 in northern Wisconsin. Of the Minnesota plots, 21 were sampled in detail by horizons, 25 were studied by composite fixed-depth samples, and 8 in young stands were sampled only for organic layers. In the remaining Minnesota plots, holes were bored in the soil for classification of soil series and type, depth to water table, and depth to mottling. Wisconsin sites were sampled by horizon. Most of the field and laboratory work was done in the period 1939 to 1942.

The soils studied include gray wooded, brown podsolic, gray-brown podsolic, and podsol soils. The climate covers a considerable range of conditions. Average annual precipitation is about 25 inches in northern Minnesota and 30 inches in northern Wisconsin. Mean annual temperatures are 36° and 40° F., respectively, in the two areas.

SELECTION OF SITES

Stands selected for study were pure or nearly pure, even-aged, well-stocked, and generally in the range of 20 to 60 years of age. Some younger stands were selected for study of the amount of forest floor present on the basis of ovendry material per acre. A few stands

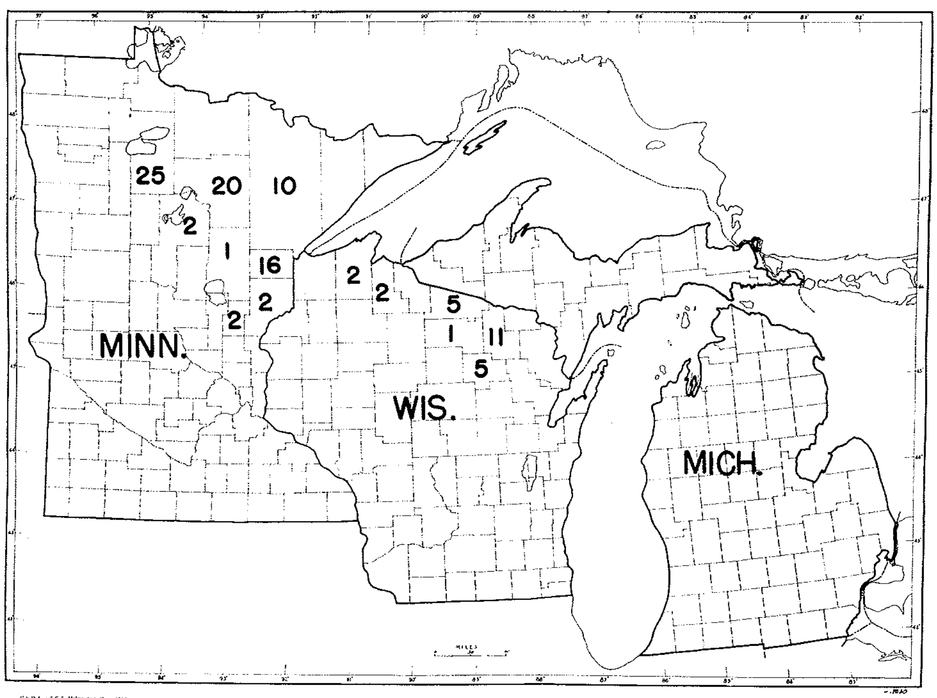

Fig. 2. Location of the sample plots. The figures represent the number of sample plots taken in each county studied in Minnesota and Wisconsin.

were older than 60 years.

The location of the plots is shown in figure 2. A deliberate attempt was made to study aspen on as complete a range of soil textures as possible, ranging from sands, loamy sands, sandy loams, loams, and silt loams through clays. Also areas were selected so as to get a sampling of soils of glacial as well as lacustrine origin, of lime-rich as well as lime-poor areas, particularly as judged by effervescence of soil samples from lower depths (2.5 to 7.0 feet) with 10 percent hydrochloric acid. Some shallow water-table areas were also sought.

No plots were taken where topography was rough or where the position on the slope or aspect would favorably or adversely affect its site index. This might have involved another half dozen variables that had nothing to do with the primary purpose of the study.

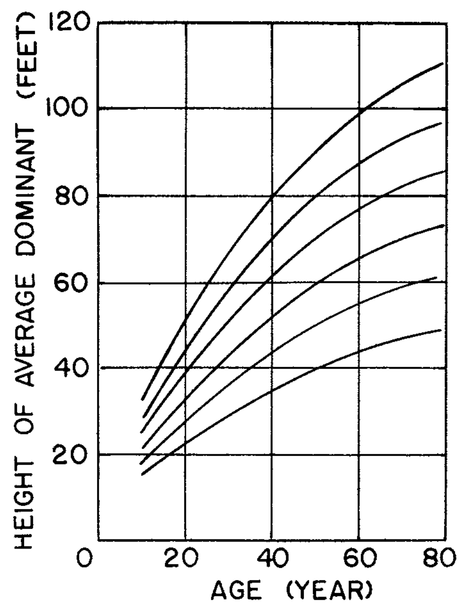

Fig. 3. Site index curves for quaking aspen in the Lake States. The curves represent site index at age 50 of 90, 80, 70, 60, 50, and 40 feet respectively. (After Kittredge and Gevorkiantz.)

DETERMINATION OF SITE INDEX AND VOLUME

Site index was determined by measuring height of from three to seven representative trees of the dominant and codominant tree classes with an Abney level. Age determinations were made either by boring these sample trees at a height of about 1 foot above ground with an increment borer and making a count of annual rings on the cores, or by actually felling the trees and counting the annual rings on the stump. Height was determined on felled trees by measurement with a tape. Site index was determined from curves of height-age relationship developed for aspen (Kittredge and Gevorkiantz, 1929) and reproduced in figure 3.

Volume was determined from a tally to the nearest 1-inch diameter class of all trees of 2-inch class or larger on the one-fifth or one-tenth acre circular sample plot where soil profile pits were dug and where soil sampling was done by horizon. The sample trees were used as a basis of drawing average height-over-diameter curves which were applied to the stand of aspen as a whole. Volumes, in terms of cubic feet inside bark to 3-inch top as well as total volume of trees 2 inches and over in diameter at breast height, were then computed for all trees on the plot; 4-inch top was used on Minnesota plots.

Some of the sample plots had a moderate volume of other tree species present besides aspen. The volume of these trees was read from composite volume tables prepared by Gevorkiantz and Olsen (1955). To obtain an overall merchantable volume figure for the plot, the volume of the nonaspen species was added to that of the aspen to give the complete picture of overall wood production.

The correlation of site index and mean annual increment on the 21 Minnesota plots where tree volumes were recorded is significant at the 1

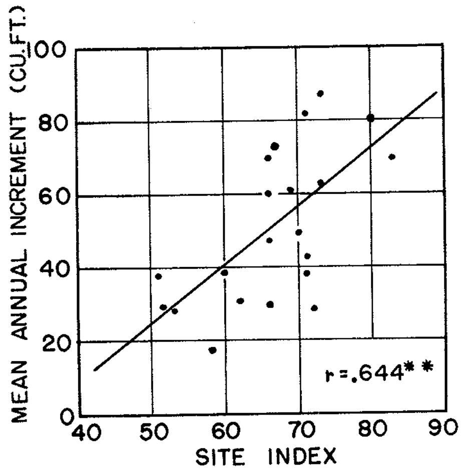

Fig. 4. Relation of site index and mean annual increment of aspen 4 inches and over at diameter breast high on 21 sites in Minnesota.

percent level regardless of which of three volume criteria are used.

Using volume of aspen 4 inches and over, the correlation coefficient is .644 (figure 4). Using all aspen of 2-inch class and over, the correlation coefficient is .621. These are not quite as high as those found in a Wisconsin study where the correlation coefficient was .923. However, all show a good relationship, and indicate that site index is a good criterion of wood production.

SOIL SAMPLING

Soils were sampled in one of two ways. On one group of 25 plots a mechanical sample was taken to a uniform depth of 36 inches from several holes bored with a soil auger and the entire sample was placed in numbered cloth bags.

On another group of 45 sample areas, the soils were sampled by horizons. The organic layers were sampled separately as duff (F) and humus (H), taking the sample usually from three to six small sampling areas of 6 by 6 inches in size, sharply defined by a steel frame.

To sample the mineral portions of the profile, a pit was dug to a depth of 4 to 5 feet, or to full depth of rooting. In some cases the pit was over 6 to 7 feet. A soil sample was taken from each horizon limiting the sample to the interior 60 to 80 percent of each horizon, and avoiding the transition zones to adjoining horizons to avoid contamination of the sample. The sample was cut or chipped out of the profile wall with a butcher knife, ice pick, and garden trowel, beginning with the lowest layers.

The notes also included information on drainage, depth to water table if closer than 8 feet, slope, and aspect. Considerable time was spent in appraising the fire history of each plot since it had been indicated in a previous study in northern Wisconsin (Stoeckeler, 1948) that repeat forest fires in established aspen stands caused a marked reduction in site index due to fire scars, destruction of part of the root system in the organic layers (notably humus), fire scarring of trees, and burning of at least part of the organic layers, with a resulting loss of nitrogen.

SOIL ANALYSIS

The soils from fixed-depth profiles were analyzed in the soils laboratory at the University of Minnesota, using standard procedures and methods. A portion of the horizon-sampled soil was run by the Soils Department at the University of Wisconsin.

Texture was determined by the Bouyoucos hydrometer method (Bouyoucos, 1927). Moisture equivalent was determined by centrifuging saturated duplicate samples at 2,440 revolutions per minute (Briggs and McLane, 1907). Total nitrogen was determined by the Kjeldahl method (Assoc. Official Agr. Chemists, 1950). Base exchange capacity was determined by leaching with ammonium acetate and subsequent distillation and titration (Chapman and

Kelley, 1930). Conductivity was determined by measuring the electrical resistance of a suspension of soil in water (Wilde and Voigt, 1955).

Available potash, calcium, and phosphorus was determined on fixed-depth samples in 25 samples from Minnesota by the Spurway method involving tests for active constituents (Spurway and Lawton, 1949).

In 24 samples from Wisconsin sampled by horizons, the tests for available calcium, phosphorus, potassium, and magnesium were made by the Hellige-Truog field test kit.

For 21 Minnesota samples sampled by horizon, available phosphorus was determined by the Truog method (Truog, 1930), and replaceable calcium, potassium, and magnesium in connection with tests for base-exchange capacity (Chapman and Kelley, 1930).

The determination of pH was made electrometrically by the Coleman or Beckman pH meter.

STATISTICAL ANALYSIS

The class of data collected made it especially amenable to appraisal by correlation analysis outlined by Snedecor (1937), and Goulden (1939). Most of these were straight-line relationships and some were curvilinear. The analyses presented in connection with a number of graphs give a correlation coefficient (r), and a double or single star after the value if significant. A double star or asterisk indicates statistical significance at the 1 percent level (odds 99 out of 100), and a single star indicates significance at the 5 percent level (odds 95 out of 100). Unstarred values are not significant at the 5 percent or 1 percent level and are labeled (N.S.) meaning nonsignificant. Standard deviations are used in connection with certain tabular data. Averaging lines for data in graphs are based on calculated regression equations.

Results and Discussion

MINNESOTA SITES SAMPLED BY A SINGLE 0- TO 36-INCH SOIL SAMPLE

One aspect of work involved a study of 25 sample plots where a composite soil sample was taken to a uniform depth of 36 inches. This was made up of a composite from several auger holes. The purpose of these 25 plots was to determine if this vastly simplified procedure would yield any meaningful relations between soil and tree growth. On these 25 plots, only site index was determined by the height-age relationship procedure already described.

The 36-inch uniform sampling depth was adopted because previous studies had shown that the root system of quaking aspen is largely confined to the top 3 feet of the soil.

Three feet of soil have a substantial field-storage capacity for soil moisture ranging from a total of 6 inches of water for sands up to 12 inches of water for clays.

Effect of Soil Texture on Site Index

Soil texture expressed as percent of silt + clay was the most meaningful soil factor in its effect on site index. It had a correlation coefficient of .715, significant at the 1 percent level (statistical odds of 99 out of 100), for the 16 plots not affected by repeat burns or by shallow water tables (figure 5). For 25 plots, ncluding 9 which had been burned since establishment of the present aspen stand or had shallow water tables, the correlations were nonsignificant ($r = .221$).

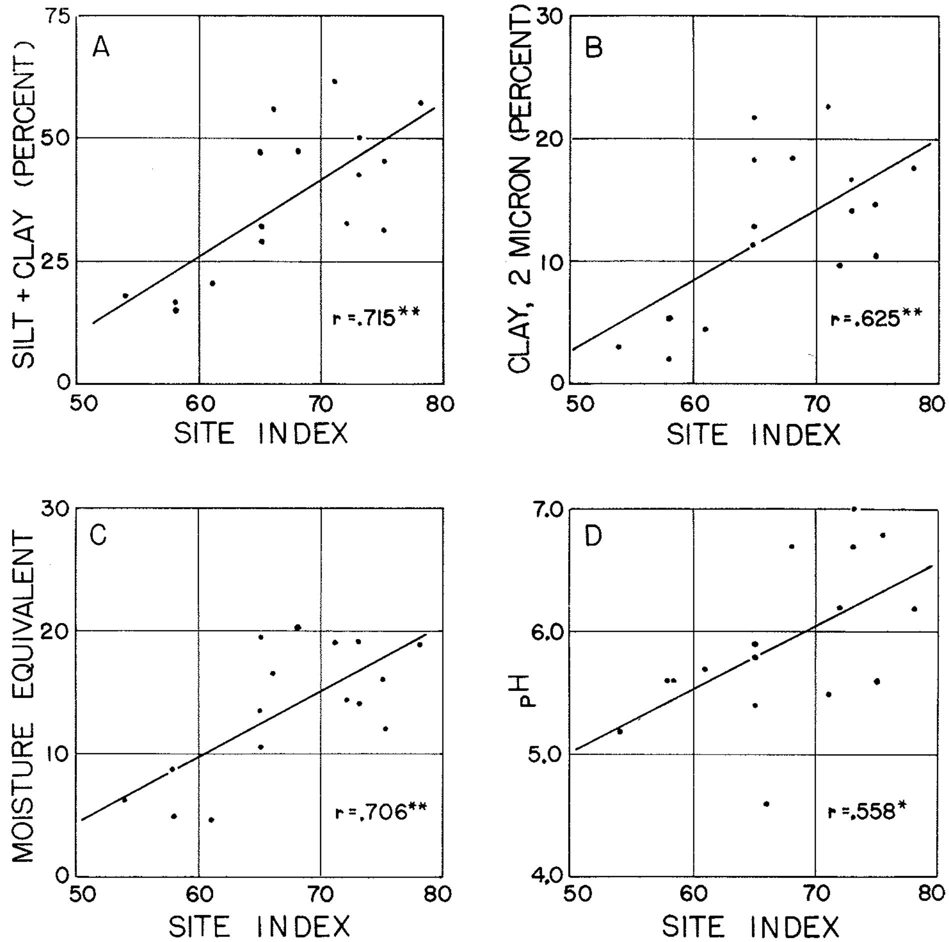

Fig. 5. Relation of soil properties and aspen site index for the 0-to 36-inch soil layer for 16 Minnesota plots without repeat burn. (A) Silt + clay; (B) 2-micron clay; (C) Moisture equivalent; (D) pH.

Shallow water tables tended to increase site index very substantially, especially on sandy or gravelly soils of rather poor water-storage capacity. Repeat burns tended to reduce site index. The same tendency of data from these 9 plots to show extreme scatter from the 16 normal, unburned plots without shallow water tables showed up in all other correlations on these 25 plots sampled by fixed depth.

The silt + clay content ranged from 15 to 62 percent, or from sands to loamy sands, sandy loams, loams, to silt loams. In a broad grouping, the sands and loamy sands combined (under 20 percent of silt + clay) had site indexes of 54 to 60, the sandy loams had site indexes of 61 to 76, and the loams or better had site indexes of 66 to 78.

Content of clay fractions (.002 mm. or less) was also significant in relation to site index of aspen at the 1 percent level of significance for the 16 plots not affected by repeat burns or shallow water tables. This data had somewhat more scatter than silt + clay and had a correlation coefficient of .625 (figure 5). For all 25 plots, including 9 burned or subirrigated plots, the correlation coefficient was not significant ($r = .115$).

Particularly signficant in the graphic presentation of the data for clay content and site index (figure 5) is the low site index of the four plots with only 2 to 6 percent of clay. Their average site index ranged from 54 to 61, in contrast with a range of 65 to 78 for plots with 10 to 23 percent of clay.

The clay content of the soil, comprising the colloidal fraction of the soil separates, can be regarded as the most important fraction because of its important role in the base-exchange complex and in water-holding capacity.

It appears evident from the trends both for silt + clay content and clay alone that good growth of aspen occurs only on soils with comparatively good moisture relations.

Effect of Moisture Equivalent on Site Index

Since texture as judged by percent of silt + clay had proved to be significant with site index, one would assume that moisture equivalent would likewise show a similar significance.

This proved to be true. The correlation coefficient for the moisture equivalent and site index relation was .706, significant at the 1 percent level (figure 5). This was almost identical to the value for silt + clay ($r = .715$) and the criteria can be assumed to be virtually identical in their general meaning in terms of moisture relations (and, indirectly, in nutrient relations). Based on all 25 plots, including 9 repeat burn or shallow water table plots, the relation was nonsignificant ($r = .346$).

The moisture equivalent values ranged from about 4 to 20. Plots with moisture equivalents in the range of 4 to 9 had site indexes in the range of 54 to 61. Those with moisture equivalents in the range of 10 to 20 had site indexes in the range of 65 to 78.

Effect of pH on Site Index

A significant relation was found between soil pH and site index, with the more acid soils having somewhat poorer site index than the slightly acid or neutral soils. The more acid soils were those more deficient in lime than the near-neutral soils. For the 16 unburned plots the correlation coefficient was .558, significant at the 5 percent level (figure 5). For all 25 plots, the correlation coefficient was .457, significant at the 5 percent level.

The six sample plots with average pH for the top 36 inches of soil in the range of 6.2 to 7.0 had an average site index of 73, while the 10 with pH in the range of 4.6 to 6.0 averaged only 64, or practically one full site index class lower, assuming 10-foot intervals between site index classes.

The pH value for the composited 0- to 36-inch depth is undoubtedly heavily influenced by the pH of the B horizon, since the B layer usually constitutes at least half to two-thirds of the total depth of soil sampled in such a composite sample.

Effect of Cation-Exchange Capacity on Site Index

Cation-exchange capacity proved to have a significant relation to site index of aspen. Based on 16 sample plots not affected by repeat burns or shallow water tables, the correlation coefficient was .632, significant at the 1 percent level (figure 6). Based on all 25 plots, the correlation coefficient was .315, and was not significant. The range of exchange capacity in the 16 unburned plots was from 3 to 16 milliequivalents per 100 grams. Plots with an exchange-capacity under 5 had a site index average of only 58; those in the 6 to 18 range averaged 70.

The correlation coefficients for clay content and exchange-capacity as related to site index were almost identical, the former being .625 and the latter .632—both significant at the 1 percent level. This verifies the well-

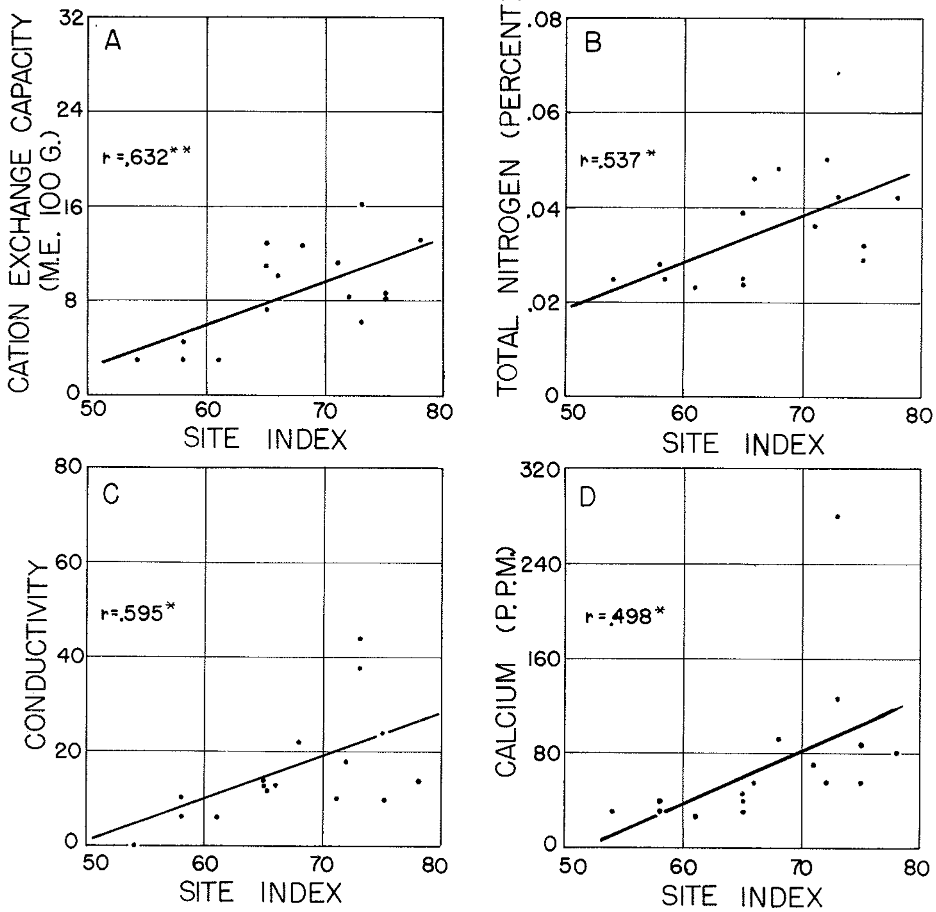

Fig. 6. Relation of soil properties and aspen site index for the 0 to 36-inch layer for 16 Minnesota plots without repeat burn. (A) Cation-exchange capacity; (B) Total nitrogen; (C) Conductivity; (D) Calcium.

known fact of close relations between colloidal soil fractions and the exchange-capacity.

Effect of Total Nitrogen Content on Site Index

Total nitrogen had a relation to site index, with a correlation coefficient of .537, significant only at the 5 percent level for the 16 plots not affected by repeat burning or shallow water tables (figure 6). For all 25 plots the correlation coefficient was .315 and was not significant.

The total range in nitrogen content for the 16 undamaged plots was from 0.023 to 0.068 percent, with most values falling between 0.03 and 0.05 percent.

Effect of Conductivity on Site Index

Conductivity gave a fair correlation ($r = .595$) with site index, being significant at the 5 percent level for the 16 plots not affected by repeat burns or shallow water tables (figure 6). For all 25 plots, the correlation coefficient ($r = .430$) also was significant statistically at the 5 percent level.

The range in conductivity was from 6 to 44, with half of the values lying between 10 and 15.

Conductivity, based on these studies, did not rank as well as cation-exchange capacity as an overall indicator of probable status of nutrients for unburned, upland well-drained sites, where r was .632, significant at 1 percent. Conductivity as an indicator of site index had about the same value as pH with very similar correlation coefficients.

Effect of Available Calcium on Site Index

Calcium content of the soil showed some relation to the site index of the aspen. The 9 plots with over 50 parts per million of calcium had an average site index of 72, while the 7 plots with less than 50 parts per million averaged only 61. The conclusion is that aspen has at least a moderately high requirement for calcium.

The correlation coefficient for the 16 undamaged plots was .498, significant at the 5 percent level (figure 6). For all 25 plots the relation was not significant ($r = .308$).

Of the four nutrient elements (N, P, K, Ca) only nitrogen showed a higher correlation than calcium in this particular aspect of the study.

Effect of Available Potassium on Site Index

There was no correlation of available potassium, expressed as parts per million and determined by the Spurway method, and site index of aspen. For 16 undisturbed plots the correlation coefficient was $-.201$; for all 25 plots it was $-.278$. The extreme range of available potash was from 8 to 54 parts per million with 80 percent of the values in the 10 to 29 range. In fact, the plots with as little as 10 to 15 parts per million of available potassium (by this testing method) had the best site index, with 6 out of 7 plots being in the range of 65 to 78 feet, averaging 71 feet in site index.

Effect of Available Phosphorus on Site Index

There was virtually no available phosphorus in the 25 profiles, based on the Spurway method; 18 profiles showed a trace, 5 had about 1 part per million, and 2 samples had 5 and 8 respectively. Readings over 5 are considered satisfactory for most crops by this testing method. Hence, there was no basis for attempting a statistical evaluation of the data. Based on these results and those on tests made on individual portions of profiles sampled by horizons, on an entirely different set of 21 plots, one would conclude that the Spurway method does not as thoroughly extract phosphorus in forest soils as does the method devised by Truog, which in the mineral portions of the profile (in A_2 and B_2), generally showed from 20 to 30 parts per million of available phosphorus for the majority of plots, with 9 of 21 having between 30 and 78 parts per million in the A_2.

MINNESOTA SITES SAMPLED BY HORIZONS

A group of 21 profiles was sampled in detail by horizons, to allow a comparison of results with those sampled by a mechanical 0- to 36-inch depth. In addition eight other plots had a record made of organic layers and thicknesses of the A horizon and its components. For analysis purposes the A_2, B_2, and H layers were selected since these were found on all the plots. The A_1 was tested only for pH and N. There was no A_1 in 13 of 29 plots where depth of A horizon components was recorded.

Effect of Depth of A Horizons

Some of the past work on relation of certain soil-profile characters to site index has indicated that depth of the A horizon may be postively correlated with site index. Auten (1937b) showed

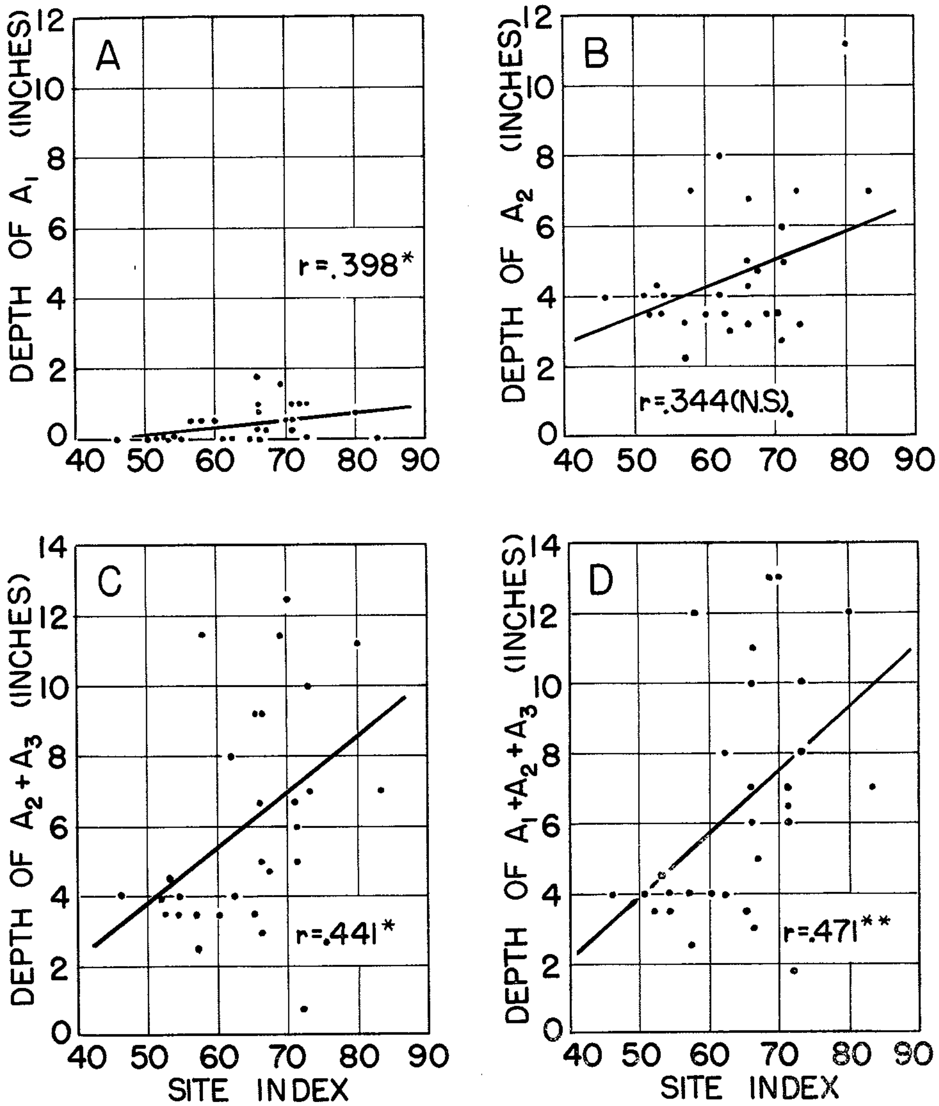

Fig. 7. Relation of depth of A horizon and its fractions to site index for 29 Minnesota sites (A) A_1 horizon; (B) A_2 horizon; (C) $A_2 + A_3$ horizons; (D) $A_1 + A_2 + A_3$ horizons.

a relation of depth of A_1 to site in yellow poplar, and Gaiser (1951) found it related to site index of oak. Kittredge (1938) made some use of the comparative development of the A_2 horizon in classifying aspen sites.

In the 29 plots where thickness of horizons was noted, an attempt was made to evaluate thickness of the A_1, of the A_2, of the $A_2 + A_3$ (in such cases where there was an A_3), and the combined thickness of all components of the entire A horizon, which included $A_1 + A_2 + A_3$ or which ever of these were present.

Depth of A_1 gave a weak correlation

coefficient of .398, barely significant at the 5 percent level (figure 7).

Depth of A_2 gave a correlation coefficient of only .344 and it was just below the 5 percent level of significance.

Depth of $A_2 + A_3$, representing the strongly leached layers, proved significant at the 5 percent level with a correlation coefficient of .441.

When the entire depth of the A horizon is considered (including $A_1 + A_2 + A_3$) the correlation coefficient was .471, significant at the 1 percent level. Individual plots, however, varied considerably from the mean. This was particularly true in the middle or upper middle range of site index, especially around 65 to 71. Here total depth of the A ranged all the way from 1.8 to 13.0 inches. Therefore, one would conclude that depth of A horizon as a criterion of site for aspen would have limited usefulness; it would, however, be helpful in helping to distinguish the poorer sites (index 46 to 55) from the better sites (70 and over). The former have a total depth of combined A horizons of 2 to 4 inches. The better sites generally had a depth of 6 to 12 inches.

Effect of Texture

The correlation of site index and soil texture expressed as percent of silt + clay content (all fractions 0.05 mm. or less expressed as a percent of that part of the soil mass passing a 2 mm. screen) was nonsignificant for the weighted average of values for the A_2 and B_2 horizons. Its lack of significance was due to presence of some plots with rather sandy soil lying over finer-textured subsoils (C_2 horizon) at a depth below 3 feet; also there were several other plots with gravel substrates below the depth of sampling. These gave unusually high site index for soils with fine-textured substrates, and low site index for plots with gravelly C_2 horizons. It indicates the need of considering the texture of C_2, as well as the solum, and setting up a penalty scale for gravel content. This is not done in the standardized Bouyoucos test for silt + clay content where the fractions above 2 mm. are discarded.

Effect of pH by Horizons

The pH in profiles sampled by horizon was more significant statistically than the values for texture. The pH of the H layer as related to site index had a correlation coefficient of .530 (figure 8,) which was significant at the 5 percent level. The pH for poor site index plots was in the range of 4.52 to 4.75 while on good sites it was in the range of 5.12 to 5.78, generally in the 5.2 to 5.6 range.

The pH of the A_2 horizon and site index gave a correlation coefficient of .618, significant at the 1 percent level. Poor sites (under 55 site index) had a pH in the range of 4.35 to 4.65. Good sites were mostly in the range of 4.90 to 5.80, with an average of about 5.35.

Effect of Cation-Exchange Capacity

Cation-exchange capacity gave no significant correlations with site index in the samples taken from the humus layer, A_2, and B_2 horizons.

The cation-exchange capacity was highest in the H layer, ranging from 11.6 to 102.0 milliequivalents/100 grams, and averaging 61.0. It was very much lower in the A_2, ranging from 1.7 to 11.0, and averaging 5.5. In the B_2, the exchange capacity was as high or higher than in the A_2 in 15 of 21 plots, ranging from 1.3 to 26.6 and averaging 11.2 m e./100 grams, or about double that of the A_2.

Effect of Conductivity

There was no significant relationship between specific conductance of the A_2. B_2, or H layers and the site index of the 21 sites. Apparently this is not a consistently meaningful indicator of the site since in the profile sampled by a mechanical 0- to 36-inch depth, conductance and site index (figure 6) were barely significant at the 5 percent level.

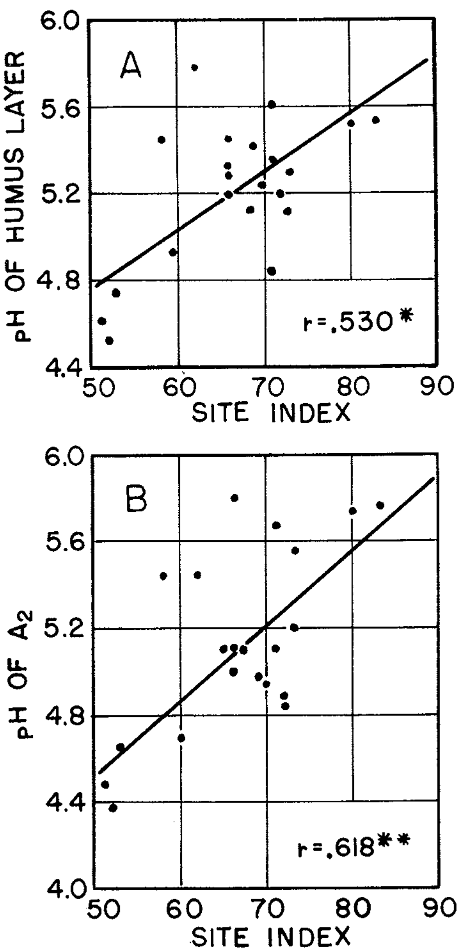

Fig. 8. Relation of soil properties and site index for 21 Minnesota plots. (A) pH of humus layer; (B) pH of A_2 horizon.

In the H layer conductivity ranged from 62.0 to 210.0, averaging 165.3. In the A_2 the range was from 7.6 to 16.8, averaging 11.1. In the B_2 the range was from 6.4 to 43.8, averaging 15.3.

Effect of Total Nitrogen

Total nitrogen content of individual horizons showed rather poor correlations with site index except in one instance. On 13 plots where the F layers were sampled a significant correlation was found with a correlation coefficient of .632, significant at the 5 percent level. Total N content ranged from 1.52 to 1.92, averaging 1.74, and was highest in the high site index plots (figure 9).

On the same 13 plots, the nitrogen content of the humus layer was substantially lower than of F layers, ranging only from 0.73 to 1.51 for the H layer. The nitrogen content of the A_1 ranged from .216 to .407 percent, averaging .329.

In the A_2, total nitrogen ranged from .017 to .074 percent, while in the B_2 the range was .010 to .060 percent.

Effect of Replaceable Potassium

Available potash and site index showed a correlation coefficient in the B_2 horizon of .431, barely missing significance at the 5 percent level, for which an r of .433 was required. The range of replaceable potassium was from 6 to 33 parts per million. The averaging line (straight line relation) passed through 7.0 p.p.m. at site index 50, to 19.5 p.p.m. at site index 80.

Effect of Replaceable Calcium

Replaceable calcium and site index had a statistically significant relationship for the B_2 horizon. The correlation coefficient was .526, significant at the

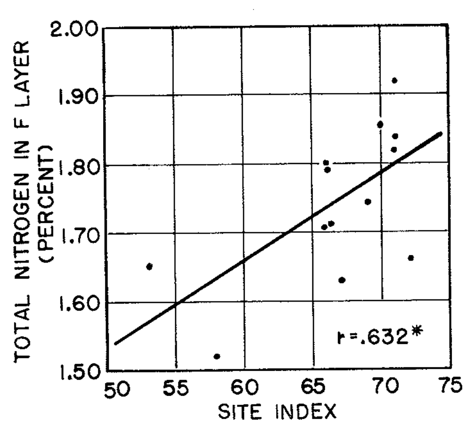

Fig. 9. Site index of 13 aspen plots in Minnesota as related to total nitrogen in the F layer.

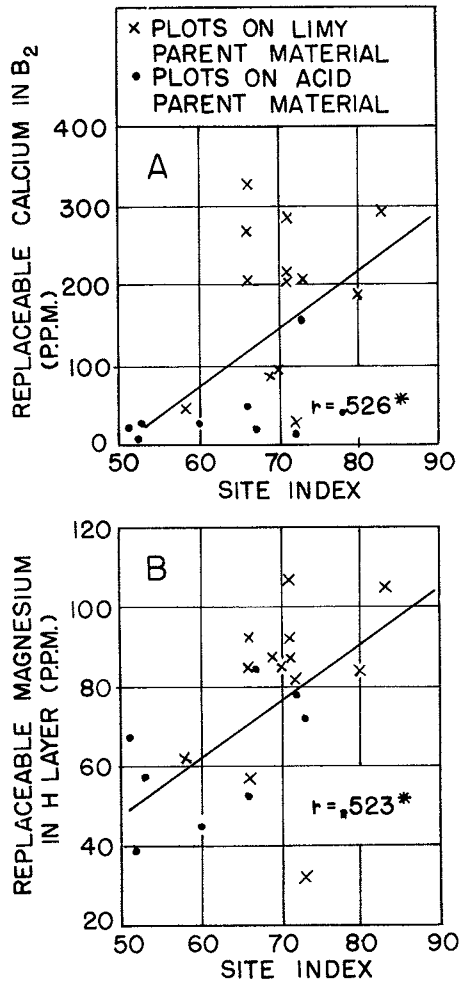

Fig. 10. Relation of soil profile properties and aspen site index for 21 Minnesota plots. (A) replaceable calcium of the B_2 horizon; (B) replaceable magnesium of the H layer.

5 percent level (figure 10). The range of values was from 13 to 325 parts per million.

The replaceable calcium was markedly lower in the B_2 in soils with acid parent material, 7 of the 8 plots ranging between 13 and 51 p.p.m. The eighth plot averaged 161. The average of replaceable calcium in the 8 plots was 44 p.p.m. In contrast, the average replaceable calcium in the B_2 of the 13 plots with calcareous parent material was substantially higher, averaging 190, with a range of 31 to 325.

Replaceable calcium in the humus layer (H) and site index of aspen were nonsignificant, yielding a correlation coefficient of .397. The range was from 290 to 1,210 p.p.m.

Effect of Replaceable Magnesium

Replaceable magnesium in the H layer showed a significant relation to site index, with a correlation coefficient of .523, significant at the 5 percent level (figure 10). Replaceable magnesium ranged from 32 to 107 parts per million. It was substantially higher in the humus layers which were developed on calcareous parent materials than on those developed on acid parent materials.

Relation of pH of the Humus Layer, A_1, and A_2 to pH of C_2

An interesting feature of the profile analysis was the markedly higher average pH of the H layer and also the A_2 in those profiles with limy parent material (C_2) than was the case of those with an acid C_2.

The pH of the humus layer was 0.41 higher in the lime-rich than in the lime-poor soils. In profiles with limy subsoils the pH of the humus averaged 5.38; in those with acid subsoils it averaged 4.97. The correlation coefficient was .558, significant at the 1 percent level (figure 11).

Likewise, there was a differential in the pH of the A_2, also affected by the character of the C_2 horizon. In profiles with lime-rich C_2, the pH of the A_2 was 5.35; in the profiles with acid C_2, the pH of the A_2 was 4.81, or with a difference of .54. The correlation coefficient was .619, significant at the 1 percent level.

The lime-rich substrates apparently have a considerable effect on improving or increasing the pH of the A_2 and humus layers. This is due to the greater base content of the leaves which on disintegration eventually form a humus

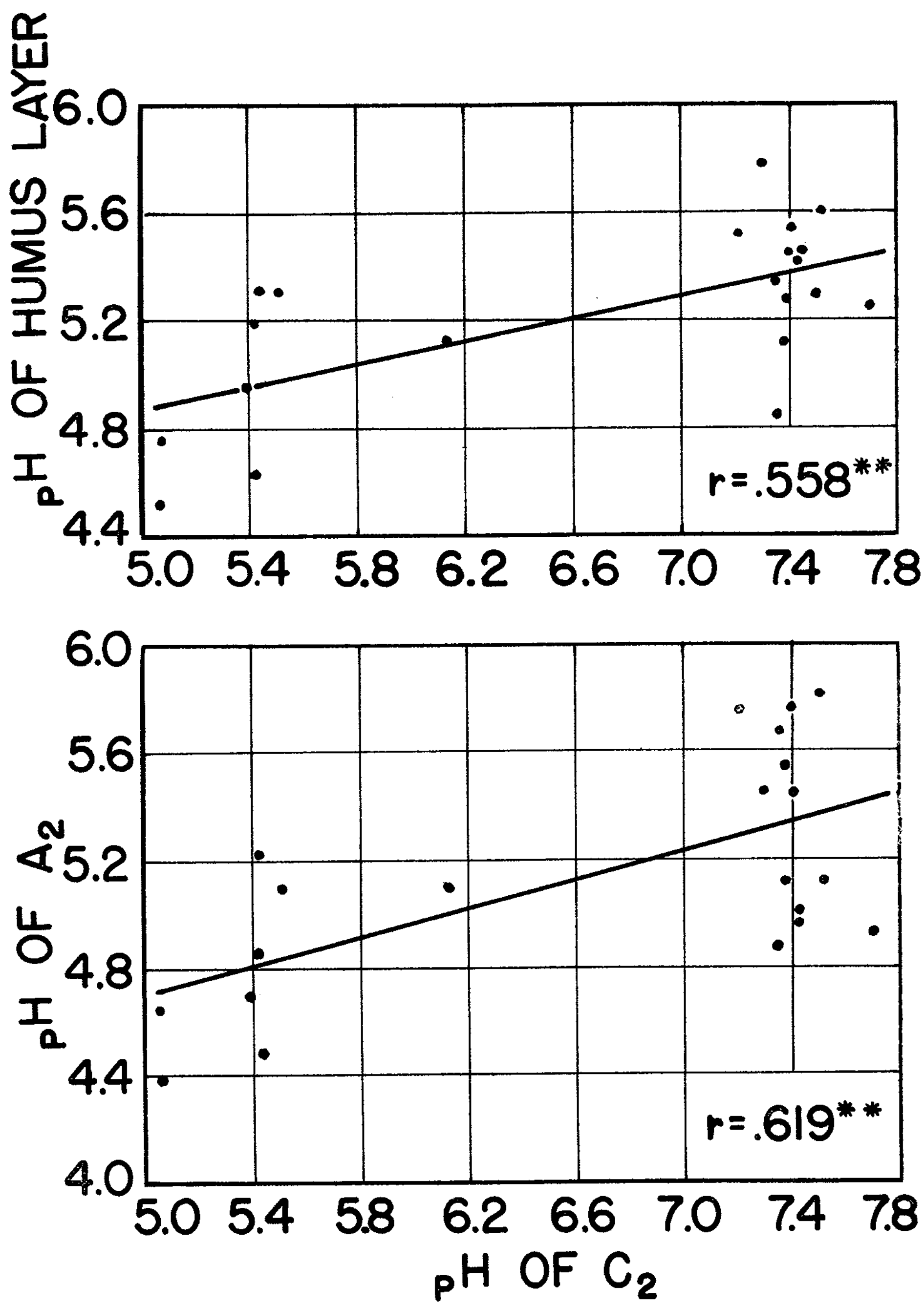

Fig. 11. The pH of the humus layer and of the A_2 horizon as affected by the pH of the parent material (C_2) of 21 aspen plots in Minnesota.

layer, and it in turn has some of its bases leached into the A_2 layer, thus increasing the pH of both these layers. The pH of the A_2 and humus layers falls into two distinct clusters of plotted points, one for the lime-poor substrates and another for the lime-rich substrates. One group centers over the 5.4 pH for the C_2; the other centers over the 7.4 pH zone.

The average pH values for the several soil horizons in 21 plots, including 14 plots where an A_1 was present, can be summarized as follows:

	Average pH of horizon		
Horizon	With acid parent material	With alkaline parent material	Difference in pH
Humus (H)	4.97	5.38	0.41
A_1	4.98	5.40	0.42
A_2	4.81	5.35	0.54
B_2	5.06	5.42	0.36

It is apparent that there is a consistent difference in pH in the entire solum as well as in the humus layer, with a higher pH in amount of about 0.4 or 0.5 in favor of those developed on lime-rich parent materials.

An interesting feature was the effect on site index of the comparative abundance of lime in the soil and as implied by pH of the C_2. In 13 of the plots with lime-rich C_2 horizons, the pH ranged from 7.2 to 7.7, averaging about 7.4 and the average site index was 70. On the 8 sites on lime-poor substrates, the pH was around 5.4, and the average site index was 62 feet, or about 8 feet less than on the lime-rich areas.

The difference in site index, however, is not attributable solely to the lime-rich substrates, because there was a texture difference in the two distinct groups of plots on which these data are based. The lime-rich group of 13, in the overall average, had more silt loam soils than the acid subsoil group of 8 plots. The site index advantage in soils of comparable texture, notably in sandy loams or loamy fine sands, was actually only about 4 or 5 feet in favor of the trees on soils with lime-rich substrates.

Rooting Habits of Aspen as Related to Soil Type and Depth of Lime-rich Substrates

A knowledge of depth of rooting and of the rooting habits of a tree species is fundamental to a better understanding of the depth to which soil should be sampled for evaluation of texture and to detect the presence or absence of lime-rich substrates within reach of the tree roots and evaluate how these may affect growth.

Data on rooting habits and depth to free carbonates was closely observed in the 21 plots where profiles were dug. The information on these is shown in figure 12.

The six soil types where carbonates were found within rooting depth are marshalled in the left part of the graph with the finer-textured soils at the left and with those that were sandier shown to the right. The profiles with considerable lime carbonates present, as detected with 10 percent hydrochloric acid, range from Beltrami silt loams through Nebish loamy fine sand.

The five soil types where no carbonates were found are marshalled in the right side of the graph, beginning with Kingsley very fine sandy loam and ranging through Munger loamy sand.

Under present day nomenclature, the soils mapped as Munger would be Chetek, the Taylor loamy very fine sand would be Grygla, and the Nebish loamy fine sand would probably be the Kinghurst series. The Kingsley series is still under consideration by soil classifiers as to its new nomenclature.

For the 9 soil types and 18 profiles where roots were traced to full depth of rooting, the average maximum depth of root penetration was 51 inches. For the 13 individual profiles where lime carbonates were found in the rooting zone, the average rooting depth was 52 inches, while the lime zone was at an average depth of 39 inches. This repre-

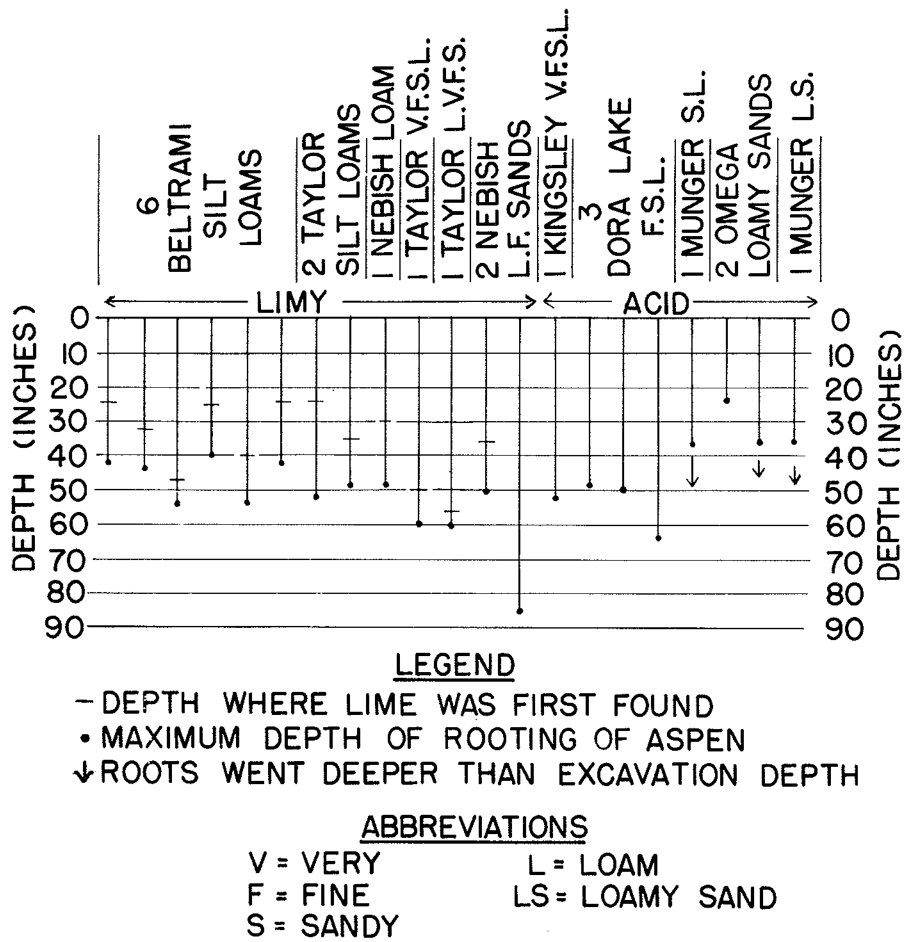

Fig. 12. Rooting depth of aspen and depth to calcium carbonate in 21 Minnesota soil profiles.

sents an average root penetration of 13 inches into soil material rich in lime carbonate. The extreme range of its penetration was from 4 to 28 inches, with most of the values being 10 inches or more. Rooting in this zone was usually rated as "slight."

The depth at which lime carbonate was first encountered and where rooting ended is shown at the bottom of figure 12. It was averaged for all the profiles within a specific soil series and texture class. For instance, in the six Beltrami silt loams the average depth of lime was 32 inches, while the rooting depth was 46 inches. At the other end of the scale there are two Nebish loamy fine sands where these average values are 58 and 67 inches respectively, indicating a 26-inch greater depth to lime in the sandier than in the finer-textured soil, while rooting depth was 21 inches deeper in the sandier than in the finer-textured soil.

For the 18 profiles dug to full rooting depth, the average depth of the zone where rooting was rated as fair or better was 38 inches.

From these data on root depth, root distribution, and depth where lime car-

Table 1. Rooting depth observed in 24 Wisconsin aspen sites, 1939-42

Soil series and types	Rooting depth Range	Average	Plot
	inches		number
Vilas and Plainfield sands and loamy fine sands	35-66	48	7
Kennan, Vilas, and Plainfield sandy and fine sandy loams	17-48	39	10
Kennan and Plainfield loams*	21-48	39	6
Superior silty clay loam		40	1

* One plot mapped as Plainfield was probably some other soil series.

bonates were first encountered, one would conclude that for most purposes examining the soil to a depth of 36 inches (a standard soil auger length) is satisfactory for estimating the general soil moisture regime of the site as judged by soil texture and its implication in water-holding capacity.

However, in soils averaging very fine sandy loams, loamy very fine sands, or loamy fine sands it would be necessary to bore to a depth of as much as 60 to 72 inches to be fairly certain of detecting whether there are lime carbonates present within rooting depth, and also to detect underlying strata of substantially higher water-holding capacity which in turn may improve the water relations of sandy surface layers. Conversely, coarse gravel or sand substrates might decrease moisture relations of the site.

Rooting depth of aspen as observed in 24 northern Wisconsin plots was in the average range of 39 to 48 inches, with sands and loamy sands averaging 48 inches, and finer-textured soils from 39 to 40 inches (table 1). The maximum rooting depth observed in any soil pit was 66 inches.

The graphic and tabular data on rooting depth are probably not true maxima. They represent the maximum found in the area where pits were dug which were invariably between trees or at a distance of at least 3 feet from the trunk. Directly under the trunk one might assume even deeper rooting.

Nutrient Requirements of Quaking Aspen

A point of interest in connection with quaking aspen is its apparent nutrient requirements, not only in connection with its growth in the field, but also when grown under nursery conditions.

To arrive at an appraisal of the apparent nutrient requirements of the species, the data for 21 Minnesota plots were segregated in three growth regime classes labelled as poor, satisfactory, and good, and the average nutrient level for N, P, K, Ca, and Mg computed, as well as exchange capacity (table 2).

It appears that total nitrogen and available phosphorus could be at rather low levels with good growth still being made by the aspen. Most striking in contrast in the analysis of good versus poor growth conditions is seen in magnesium (ratio about 8 to 1) and calcium (ratio almost 6 to 1). It is believed that

Table 2. Levels of soil fertility as related to growth of quaking aspen*

Growth of aspen	Total nitrogen	Available phosphorus	Repl. potash	Repl. calcium	Repl. magnesium	Cation-exchange capacity
	percent	p.p.m.	p.p.m.	p.p.m.	p.p.m.	m.e./100 g.
Poor	.034	27	9	29	4	6
Satisfactory	.034	32	11	103	18	10
Good	.040	29	14	162	33	12

* Based on 5, 8, and 8 plots respectively in poor, satisfactory, and good growth conditions. The site index classes of the three groups on which these were based are: under 60, 61 to 70, and over 70 feet. The average site index was 55, 66, and 74 respectively for the three groups.

the comparatively high content of mineral nutrients, especially Ca and Mg, and possibly to some extent of K, contributes to the longer life span, greater growth rate, and lower incidence of heart rot found in aspen growing on gray-wooded soils of Minnesota. It gives them an advantage over the aspen growing on soils whose parent material is poor in content of these elements, as is rather more common in the soils of northern Wisconsin.

The extreme contrast in calcium and magnesium content in good versus poor conditions of growth leads to the conclusion that these are the two nutrients that would probably have to be supplied in comparatively large amounts in nursery (or field) fertilization to achieve high growth.

Dolomitic limestone would meet this requirement. If N, P, or K were applied the amounts apparently could be rather small. It is probable that the release of large quantities of available calcium and magnesium as an aftermath of forest fires tends to favor the rapid growth of aspen, especially if these are of seedling origin.

The contrast in pH in good versus poor sites was rather minor in these plots, being 5.0 for the poor plots and 5.3 for the satisfactory and good growth conditions. However tests on some mechanically sampled plots (0-36 inches) in Minnesota showed somewhat higher growth at pH of about 6.0.

It appears that a fairly wide latitude of pH is at least permissible with aspen in the range 5.3 to 6.5.

WISCONSIN SITES SAMPLED BY HORIZONS

In the plots sampled in Wisconsin, texture was determined by the Bouyoucos hydrometer method, moisture equivalent by the standard centrifuge method, pH by means of a Coleman portable electric pH meter, total nitrogen by the Kjeldahl method, and tests for P, K, Ca, and Mg by use of the Hellige-Truog field test kit. Soil samples were taken by separate horizons and analyzed separately and weighted averages computed for A + B horizons.

Of the various tests, those dealing with physical properties appeared to be somewhat more meaningful than the chemical properties. The deleterious effect of repeat burns verified results obtained in Minnesota.

Effect of Soil Texture on Site Index

Texture of the A + B horizons on 24 plots, based on the weighted average (weighted by depth of horizons) content of silt + clay had a correlation coefficient of .704, significant at the 1 percent level. The relationship was slightly curvilinear, with sites with 10 percent of silt + clay having a site index of 55, those with 30 percent having a site index of 66, and those with 70 percent of silt + clay having a site index of 79 (figure 13).

The correlation coefficient improved substantially when plots were segregated into unburned and repeat burn classes. The correlation coefficient for 15 unburned plots was .882; for 9 burned plots it was .894. Both are significant at the 1 percent level. The trends are curvilinear (figure 13).

Of particular interest is a comparison of the apparent deleterious effect on site index of the aspen due to repeat burning. This is summarized in the tabulation below:

Average silt + clay content of A + B horizons	Site index from the curves: Unburned plots	Site index from the curves: Repeat burn plots	Difference attributed to adverse effect of repeat burn
10	58	45	13
20	67	53	14
30	74	60	14
40	79	65	14
50	82	70	12
60	82	74	8
70	81	76	5
80	77	77	0

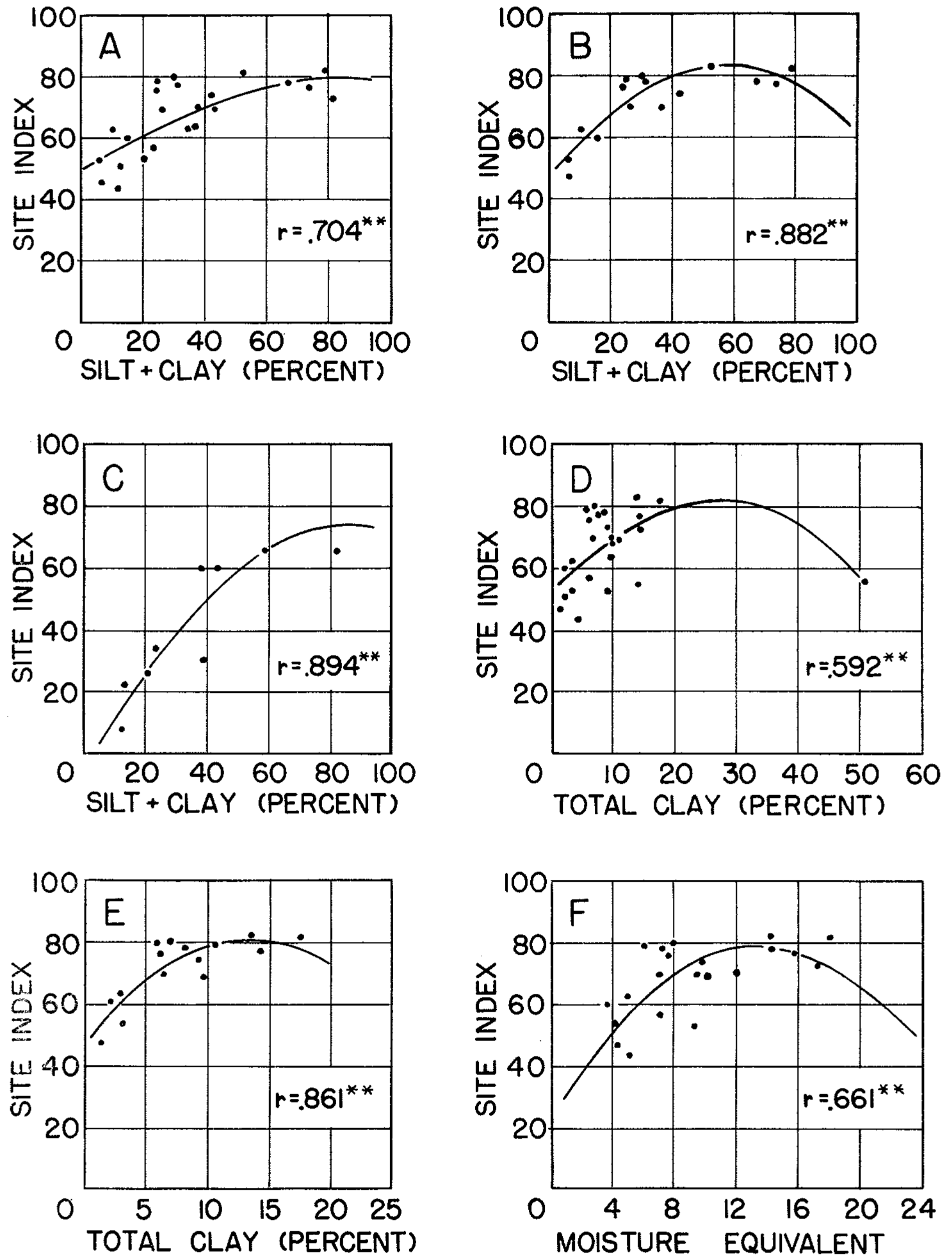

Fig. 13. Relation of soil properties for the combined A + B horizons and site index for Wisconsin aspen plots. (A) Silt + clay for 24 plots; (B) Silt + clay for 15 unburned plots; (C) Silt + clay for 9 repeat burn plots; (D) 5-micron or less fractions for 25 plots; (E) 5-micron or less fractions for 15 unburned plots; (F) Moisture equivalent for 21 plots.

From the above average values, one notes a depression of growth amounting to as much as 13 or 12 feet in site index, i.e., height growth, due to repeat burns on the sands, loamy sands, and sandy loam soils. The adverse effect appeared to be somewhat less in the heavier soils with better moisture relations. In this group of Wisconsin plots, aspen appeared to have more recuperative powers on such soils or the damage to the trees themselves or to soil nutrients is a less critical matter in terms of growth of the aspen subsequent to a repeat burn.

There was also found a positive correlation of site index with average content of soil particles of 5 microns or less of the A + B horizons. The points had considerable scatter from the weighted average curve (figure 13) and there were no values between 20 and 50 percent of clay content of 5 micron size or less. The correlation coefficient was .592, significant at 1 percent. The distribution of the points on the graph indicates a marked superiority in site index on those profiles with about 15 percent of clay compared to those with around 5 percent.

Since the correlation coefficient for the total silt + clay content is .704 as compared to .592 for clay content only for the comparable lot of plots, there seems to be ample reason for using the former as a criterion of aspen site potential rather than the latter which involves more time for analysis.

When comparing only the 15 unburned plots the correlation coefficients were remarkably close for silt + clay, compared with only the fraction of 5-micron size or smaller, i.e., .882 for the former and .861 for the latter (figure 13).

Effect of Moisture Equivalent on Site Index

The moisture equivalent which ranged from 3 to 18 had a positive correlation with site index of the aspen. For 21 plots on which the value was determined (excluding one shallow water table plot, several very heavy repeat burn plots, and a heavy clay plot) the correlation coefficient was .661, significant at the 1 percent level. The individual plot data for moisture equivalent given in figure 13 gives a slightly lower correlation coefficient than that for silt and clay content, where it was .704. The close agreement in the two values verifies the interchangeability of these two soil tests as regards their being good criteria of soil moisture relations in upland well-drained aspen sites.

Their value of .661 for the Wisconsin sites is in fairly close agreement with that found for 16 unburned sites in Minnesota which had a correlation coefficient of .706, both significant at the 1 percent level.

Depth of H Layer and Site Index

The depth of the humus layer (H) was recorded on 21 Wisconsin plots to the nearest one-quarter inch. The depths ranged from one-fourth inch to one inch, and were recorded to the nearest one-fourth inch in the field.

The correlation coefficient was .486, barely significant at the 5 percent level. There was considerable scatter in the points (figure 14) and only the plots

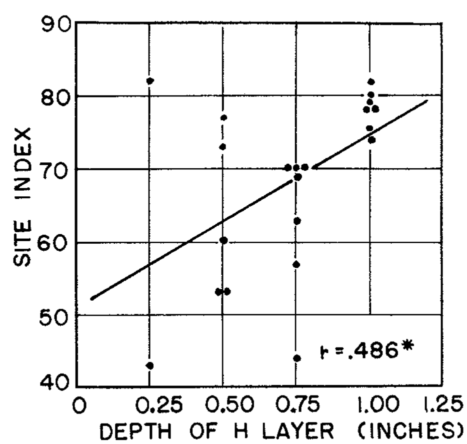

Fig. 14. Relation of depth of humus (H) layer to site index of 21 Wisconsin aspen plots.

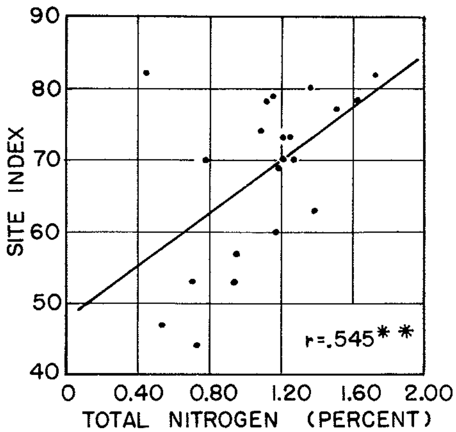

Fig. 15. Relation of total nitrogen content of humus (H) layer and site index of 21 Wisconsin aspen plots.

with about 1.0 inch depth of humus layer showed a close grouping in site index. Depth of humus layer hence does not seem to be a particularly reliable clue as to site index, especially for any single plot.

Nitrogen Content of Organic Layers in Relation to Site Index

The total nitrogen content of the humus layer ranged from 0.52 to 1.71 percent and had a significant relation to the site index of aspen of 21 plots (excluding one shallow water table plot, several very heavy repeat burn plots, and a heavy clay plot). The correlation coefficient was .545, significant at the 1 percent level. Total nitrogen ranged from 0.44 to 1.71 percent.

Total nitrogen of the humus layer (figure 15) yielded the highest correlation coefficient of any single criterion of nutrient level, involving total N, or available P, K, Ca, or Mg. The latter four were determined by the Hellige-Truog quick test method.

Strangely, there was no correlation of site index with the total nitrogen

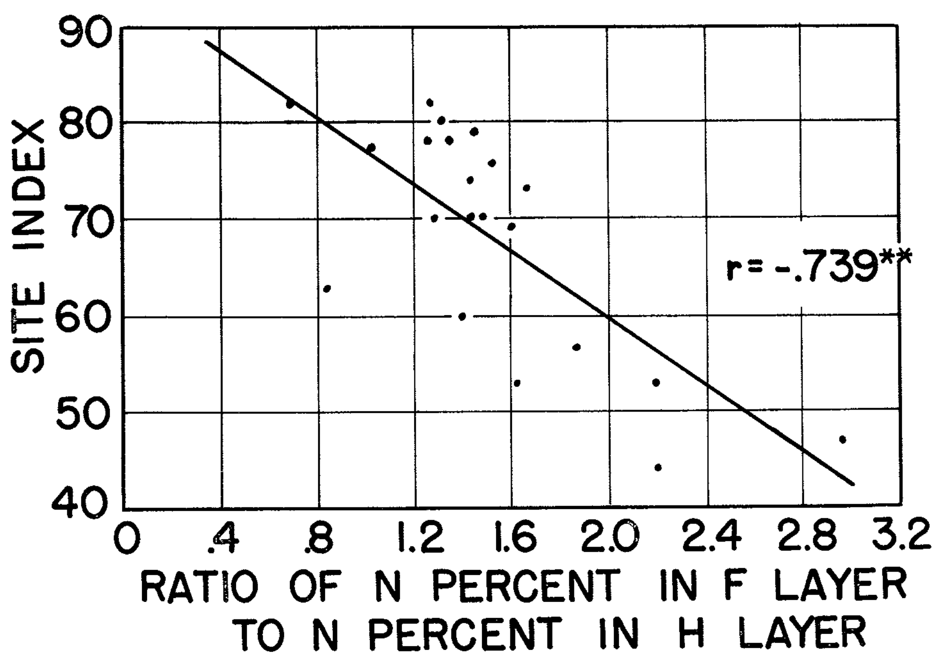

Fig. 16. Relation of total nitrogen content of duff (F) layer to total nitrogen content of humus (H) layer of 21 Wisconsin aspen plots.

content of the F layer of the identical 21 plots referred to above. The r value was —.087. One may assume that season of sampling and amount of rainfall in the period between litter fall and its sampling may have a marked effect on the N content of litter, with more fluctuation probable than in the thicker and more decomposed H layer.

However, one relationship which proved highly significant was the ratio of total nitrogen percent in the F layer to the total nitrogen percent of the H layer. The correlation coefficient was —.739, significant at the 1 percent level (figure 16). Based on the weighted average line for high site index plots the ratio of total N in the F to H layer was about 1.0 or slightly higher, while for the poor site index plots the ratio was about 2.0 or higher. This might imply that there is a differential in either the rate of nitrogen transformation, or its leaching, in high versus low site index plots.

Relation of Site Index to Mean Annual Increment in Cubic Feet

A point of interest in the evaluation of various soil properties and their relation to the growth of aspen is the problem of the relative merits of site index as a criterion of productivity versus the actual volume of wood produced, expressed as cubic feet per acre per year.

The data for 24 Wisconsin aspen plots showed a correlation coefficient of .923 between site index and growth (figure 17), significant at the 1 percent level. Volume was based on merchantable volume of trees 4 inches and over with top diameters of 3 inches inside bark, with cull due to rot or other defect deducted.

This very good relationship proves that site index, based on a height-age relationship of dominant and codominant trees and volume growth on reasonably well stocked stands, is a good criterion of the wood-growing

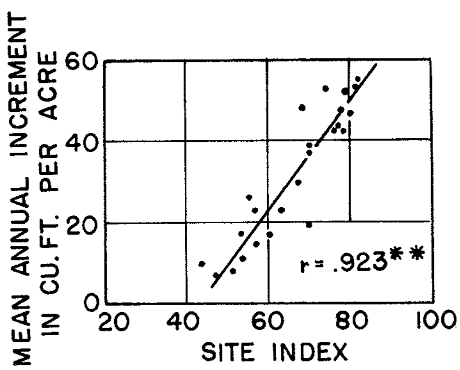

Fig. 17. Relation of site index of and mean annual increment in cubic feet per acre of 24 Wisconsin aspen plots.

potential of soil. It is easier for field men to use in the forest because only about three to seven trees need be measured for determination of average age and height. In case volume is used, a 100 percent tally of all trees on a one-fifth or a one-tenth acre plot must be made by diameter classes, age must be determined, and volume computed either from individual volume of each tree based on diameter and number of merchantable 100-inch bolts or on a height-diameter curve for the plot as a whole and diameter of individual trees.

OVERALL RESULTS FOR ALL PLOTS IN NORTHERN MINNESOTA AND NORTHERN WISCONSIN

When the data for 24 Wisconsin plots are added to the 46 from Minnesota, they provide the basis for three curves relating soil texture to site index (figure 18). It is seen that the basic curve (A) for unburned upland plots shows a site index of about 57 feet for a soil with only 10 percent of silt + clay attaining a peak of around 77 for soils with around 60 to 70 percent of silt + clay.

When all three curves are placed on the same graph (figure 19) it is seen

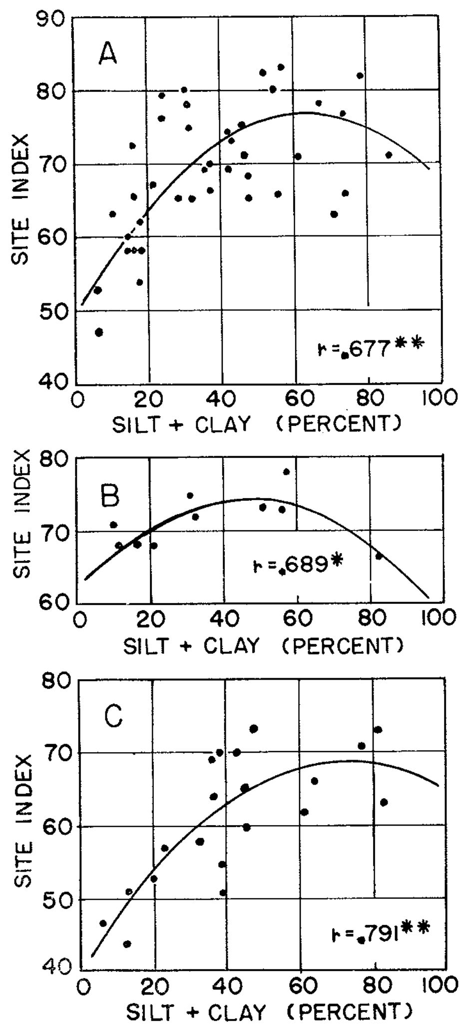

Fig. 18. Relation of silt + clay content of the soil profile to site index of 70 aspen plots sampled in Minnesota and Wisconsin. (A) for 40 unburned upland plots; (B) for 10 unburned plots with shallow water table; (C) for 20 upland plots with repeat burn by forest fires.

that shallow water tables increase site index by about 10 feet for droughty sandy soils with only 10 percent of silt + clay and that water table benefits disappear with soils with around 43 percent or more of fine material (B). On heavy soils, a shallow water table shows some tendency to slightly reduce site index.

Repeat burns appear to reduce site index by about 10 feet for the texture range from 10 to 60 percent of silt + clay. The major curves (A and C) tend to be skewed or asymmetrical, indicating that an increasing content of silt + clay benefits aspen sites only up to about 60 to 70 percent (i.e., a good loam or silt loam texture). Thereafter it is downward in trend, apparently due to high clay content of the soil and its adverse effect on permeability, aeration, and penetrability to roots.

Soils used as a basis for figures 18 and 19 were largely sampled by profile, i.e., about two-thirds were based on a weighted average silt + clay content of the A + B horizons and one-third were based on a mechanical sample of the 0- to 36-inch depth.

In the summer of 1955 there was an opportunity to examine an additional group of plots on which soil series and type and site index were obtained with a view toward getting more samples to evaluate effect of poor drainage, poor aeration, and gravelly substrates. These were pooled with the results of the plots mentioned previously.

The overall results for 103 plots of quaking aspen taken in northern Minnesota and northern Wisconsin are given in table 3. It excludes one woody

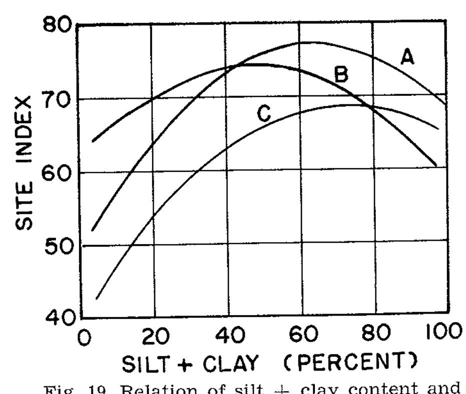

Fig. 19. Relation of silt + clay content and site index of 70 aspen plots in Minnesota and Wisconsin: (A) for 40 unburned upland plots (r = .677**); (B) for 10 unburned plots with shallow water table (4 = .689*); (C) for 20 upland plots with repeat burn (r = .791**).

peat plot whose site index was 65, and which had 8 feet of woody peat over 16 inches of sand which lay over sandy clay. The water table was at 24 inches below the surface.

Table 3 is divided into 30 major groups with two of them split into two subdivisions of two classes each, making a total of 32 groups. Of these, 19 have data as follows: (a) average site index with its standard deviation; (b) number of plots, in parentheses; and (c) site index represented by Roman numerals. For the 13 groups where no data were available an estimate of the site index is given.

The most important data are contained in the first column for 62 well-drained upland plots. For the five major soil texture groups, it is noted that site index improves by about one site class for each increase in texture group up to the 50 to 70 percent of silt + clay group. Thereafter it drops off slightly to site class II. Rather sandy soils with heavy subsoils are improved by about 12 feet in site index due to the improved water relations of such soils. Their nutrient relations are also better than soils underlain by sands.

Table 3. Site index on 103 plots of quaking aspen on mineral soil in northern Minnesota and northern Wisconsin as affected by soil texture, water tables, character of substrates, and fire history*

	No repeat burns					
	Uplands, water tables deeper than 8 feet			Shallow water tables¶		
Silt + clay in top 36 inches†	Well-drained‡	Poorly drained (poorly aerated)§	Droughty, gravelly in subsoil‖	Water tables at 2.5 to 8 feet	Water tables closer than 2.5 feet	Repeat burns, well-drained uplands
0 to 10	48 ± 3.6 (3) IV	III	V	II	III	V
10 to 20 Uniform texture to 5 ft.	58 ± 4.5 (16) III	III	V	70 ± 5.7 (5)	59 (1)	51 (1)
With heavy subsoils	70 ± 2.2 (4) II			II	III	IV
20 to 50	70 ± 4.6 (26) II	III	20 to 30 51 ± 5.1 (8) IV 30 to 50 III	69 ± 7.4 (3) II	III	61 ± 3.8 (6) III
50 to 70	76 ± 7.3 (6) I	59 (1) III	II	75 ± 2.9 (3) II	IV	63 ± 3.7 (3) III
Over 70	73 ± 5.8 (7) II	57 ± 4.3 (5) III	II	66 (1) II	IV	64 ± 5.8 (4) III
Total number of plots	(62)	(6)	(8)	(12)	(1)	(14)

* Site classes I, II, III, IV, V represent site classes 80, 70, 60, 50, and 40 respectively predicted at age 50 (Kittredge and Gevorkiantz, 1929).
† By Bouyoucos hydrometer method.
‡ No strong mottling within 12 inches of surface; usually deeper than 24 inches.
§ Strong mottling within 12 inches of surface.
‖ Droughty gravel is within 2 to 3 feet of surface of soil and gravel is 3 feet or more deep. Will also include soils where content of large rock is over 50 percent by volume of top 3 feet of soil mass.
¶ As observed in summer or fall months.
Table gives site index, and standard deviation; number of plots are in parentheses; Roman numerals are site class—actual or projected.

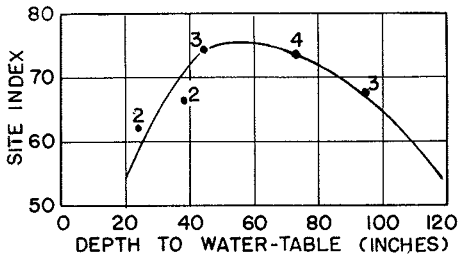

Fig. 20. Relation of depth of water table and site index of quaking aspen for 14 plots in northern Minnesota and northern Wisconsin. Figures on curve represent number of plots averaged for that point. The average site index of such plots on uplands of this texture and not benefited by water tables was 60 feet.

Poorly aerated soils, as judged by strong mottling within 12 inches of the surface, are from 16 to 17 feet poorer in aspen site index than well-aerated soils in comparable texture groups. Depth to mottling or to gleyed horizon have been used by Coile (1952) and Aird and Stone (1955) as indicators of aeration and permeability.

Droughty soils with a high gravel content in the surface layers or within a few feet of the surface (in case of soils which ran from 20 to 30 percent of silt + clay in the surface soils) were a full two site classes (19 feet) lower than soils with finer-textured substrates of adequate water-holding capacity, i.e., at least no coarser than sands.

Shallow water tables at a depth of 2.5 to 8.0 feet appeared to be of benefit to aspen only in sands and loamy sands (soils of rather low water-holding capacity). In such cases, they were about 12 feet higher in site index, i.e., 70 versus 58. Shallow water tables too close to the surface (especially those closer than 2.5 feet) apparently resulted in such poor aeration that the improved water relations of the site were offset by the poorer aeration. In one plot the water table was found at a depth of 20 inches and strong mottling was found at 2 inches below the surface of the soil. The plot was located on a Salol loamy fine sand.

The overall effect of shallow water tables on site index of quaking aspen is given in figure 20 for 14 plots. It is seen that considerable benefit of shallow water tables occurs when it lies between 2.5 and 8.0 feet below the surface with an optimum effect at 4.0 to 6.0 feet. The overall average site index of the 14 plots was 70 feet and the average expected site index from soils of this texture (when without benefit of water table) was 60. This indicates one full site index class (10 feet) improvement due to the presence of shallow water tables. The water table depths referred to are those which prevailed in mid-summer or late summer when they are usually at an average for the growing season. In spring, water tables in the northern Lake States are usually from 1 to 2 feet higher than in late fall (late October to November).

The optimum depth of a water table probably varies somewhat by texture, but the limited number of plots with shallow water tables excluded the possibilities of making a further separation.

The impact of repeat burns, at least for well-drained upland soils, can be seen by comparing the first and last columns of data in table 3. For the overall comparison, there is a weighted average difference of 10 feet in site index for the 14 repeat burn plots compared with plots not subject to repeat burns.

Summarizing table 3, one notes that silt + clay content is the prime factor on which site index is based. This single factor combines in it not only an estimate of the water-holding capacity of the soil, but also it is related to nutrients; i.e., usually the higher the silt + clay content the higher the content of N, P, K, Ca, and Mg. Modifying factors are texture of subsoil, water-table depth, fire history, and comparative aeration as judged by depth to strong mottling.

A simplified guide for estimation of site index of quaking aspen in northern Minnesota and Wisconsin is given in table 4, with deductions or increases for five modifying factors given in the footnotes. In the table, the approximate site index has been set at the average for site classes I through V, with the average at 80, 70, 60, 50, and 40 for site I, II, III, IV, and V respectively. The presence of lime-rich parent materials appears to account for only about one-half of a site index class (5 feet) of advantage over acid parent material soils or in terms of wood production, about 10 to 15 percent at age 40 or over. The advantage of lime-rich substrates shows up most effectively in soils with sandy surface textures, but these often have heavier parent material which also improves their moisture relations.

Topography, slope, and exposure have not been considered in the table since the plots used in this study were limited rather exclusively to terrain where these factors would have a minimum of effect.

Table 4. A simplified guide for estimation of site index of quaking aspen in the northern part of the Lake States based on soil texture and five modifying factors*

Silt + clay content	Site class	Approximate site index of the class for well-drained upland soils
Under 10	4	50
10-20	3	60
20-50	2	70
50-70	1	80
Over 70	2	70

* Modifying factors work as follows: assume a factor reduces the site index given in the table by one and one-half classes or 15 feet. If the table gives a value of 2, the corrected value considering the modifier is site 3.5 or site index 55. If the factor adds 1 site class or 10 feet, a value of 2 in the table becomes site 1 or a site index of 80. The factors are:

A. In case of moderate to severe repeat burn reduce table values by 1 site class or 10 feet.
B. For plots with poor drainage as exhibited by strong mottling within 12 inches of surface in soils of about 30 percent or higher silt + clay content, reduce site by one and one-half classes or 15 feet.
C. For soils with 5 to 20 percent of silt + clay content in surface 2 to 3 feet, underlain by distinctly heavier soils of substantially higher water-holding capacity (i.e., with 30 to 90 percent of silt + clay), add 1 site class or 10 feet to value in table.
D. For soils with 2 feet or less of top soil (of 50 percent or less of silt + clay) underlain by coarse gravel, reduce site by 2 classes or 20 feet.
E. For sandy soils (3 to 30 percent of silt + clay) with a shallow water table at 2.5 to 8.0 feet, add 1 site index class or 10 feet.

From general observations on effect of exposure and sites on a separate study in paper birch-aspen sites, it appears that plots on top of narrow ridges or knolls (about 150 feet or less in minimum width) and lying at least 20 feet above the level of the surrounding terrain will be from one to one and one-half site index classes (10 to 15 feet) poorer than plots on soils of similar texture located on level to undulating terrain. Likewise plots lying in the upper half of slopes at least 100 yards long and on southeast, south, southwest, or west facing slopes of about 30 percent or more slope would probably have a reduction in site index of about one full class, i.e., 10 feet.

In the course of the study as many as possible of the soils were identified as to soil series, as well as type. Data on a total of 74 plots where no severe repeat burns had occurred are given in table 5, for 26 soil series. They are arranged in alphabetical order. It is quite apparent that there is quite a wide variation of site index between soil types. The variation found within a single soil type was rather small, since the standard deviations of those types represented by 5 or more plots were in the range of ±3.7 to ±4.3 or an average of ±4.2 for the 31 plots involving 5 soil series and types. This indicates that soil series and type combined can pinpoint site index of aspen within rather narrow limits, entirely acceptable for forest management purposes and for purchase of forest land to be managed for aspen production. Hence detailed soil maps, such as are made on a county basis, provide an excellent means for the forest manager in judging the site potential of land for aspen.

Unfortunately, not much of the forest area of the Lake States has been mapped in detailed soil surveys, and site evaluation will have to depend on

Table 5. Site index of 74 unburned quaking aspen plots in northern Minnesota and northern Wisconsin as related to 26 soil series and to soil types within these series

	Special character* of soil profile					Soil type†								
Soil series	Calc.	Grav.	Poor aer.	Sand over clay	Heavy clay	Sand	Loamy sand	Sandy loam	Loam	Silt loam	Silty clay	Clay	Peat	Number of plots‡
Beltrami	x	...	...	...	...	...	...	...	...	72	...	...	...	6
Cass Lake	...	...	...	...	...	56	...	...	...	...	...	...	...	2
Cooks	x	...	x	...	...	...	...	...	...	...	65	...	...	1
Dora Lake	...	...	...	...	...	...	69	67	...	...	...	...	...	2,2
Freer	...	...	x	...	...	...	...	...	...	59	...	...	...	1
Freon	...	...	...	...	...	...	...	65	68	...	...	...	...	1,1
Grygla	x	...	...	x	...	...	67	...	...	...	...	...	...	1
Gudrid	x	...	...	x	...	...	70	...	...	...	...	...	...	1
Hibbing	...	...	...	...	x	...	...	...	...	...	54	...	...	1
Highwood	...	...	...	...	...	...	66	...	...	...	...	...	...	1
Kennan	...	...	...	...	...	...	...	75	82	76	...	...	...	7,1,3
Kingsley	...	...	...	...	...	...	...	73	...	...	...	...	...	1
Munger	...	x	...	...	...	...	53	52	...	...	...	...	...	1,1
Nebish	x	...	...	...	...	...	64	75	71	...	...	...	...	7,1,5
Nymore	...	...	...	...	...	...	58	...	...	...	...	...	...	1
Omega	...	x	...	...	...	...	57	66	...	...	...	...	...	6,1
Ontonagon	x	...	...	...	x	...	...	...	...	...	...	58	...	1
Peat (woody)	...	...	...	...	...	...	...	...	...	...	...	...	65	1
Plainfield	...	...	...	...	...	...	56	68	...	...	...	...	...	4,2
Salol	x	...	x	...	...	...	59	...	...	...	...	...	...	1
Scandia	...	x	...	...	...	...	...	46	...	...	...	...	...	1
Shooks	x	...	x	...	...	...	...	...	...	55	...	...	...	1
Superior	x	...	...	...	...	...	...	...	...	82	...	57	...	1,1
Taylor	x	...	...	...	...	...	...	...	...	66	...	...	...	1
Todd	...	x	...	...	...	...	...	43	...	...	...	...	...	1
Vilas	...	x	...	...	...	...	48	63	...	...	...	...	...	2,2

* As follows:
Calc. means calcareous parent material which is favorable for growth of aspen.
Grav. means high content of gravel or coarse sand especially in subsoil; unfavorable.
Poor aer. means poor aeration as judged by mottling within 12 inches; unfavorable.
Sand over clay means 2 to 3 feet of sand over clay; favorable.
Heavy clay means unfavorably high content of clay in solum—usually over 45 percent of 2 micron clay; unfavorable.
x means soil has that characteristic.

† A line under site index average means all plots in that average had shallow water table at 20 to 96 inches—favorable in sands and loamy sands if at depth of 3 to 7 feet.

‡ In order from left to right for the soil types with entries.

Table 6. Summary of relationships of soil and organic layer tests to site index of aspen or other criteria, Minnesota and Wisconsin

Relationship of	Minnesota plots				Wisconsin plots		Both states combined	
	Mechanical 0-36" sample		Sampled by horizon		Sampled by horizon		Both mechanical and horizon sampling	
	r	No. plots	r	No. plots	r	No. plots	r	No. plots
Silt + clay and site index	.715**	16	N.S.	21	.704**	24	.677**	40
Silt + clay and site index	......	......	......	......	.882**	15	.689*	10
Silt + clay and site index	......	......	......	......	.894**	9	.791**	20
5-micron fractions and site index	......	......	......	......	.592**	25	......	......
5-micron fractions and site index	......	......	......	......	.861**	15	......	......
2-micron clay and site index	.625**	16	......	......	......	......	......	......
Moisture equivalent and site index	.706**	16	......	......	.661**	21	......	......
Cation-exchange capacity and site index	.632**	16	N.S.	21	......	......	......	......
pH of soil and site index	.558*	16	.618**	21	......	......	......	......
pH of soil and site index	.457*	25	......	......	......	......	......	......
pH of humus and site index	......	......	.530*(H)	21	......	......	......	......
Total nitrogen and site index	.537*	16	.632*(F)	13	.545**(H)	21	......	......
Conductivity and site index	.595*	16	N.S.	21	......	......	......	......
Conductivity and site index	.430*	25	......	......	......	......	......	......
Calcium and site index	.498*	16	.526*	21	N.S.	21	......	......
Magnesium and site index	......	......	.523*(H)	21	N.S.	21	......	......
Potash and site index	N.S.	16	N.S.	21	N.S.	21	......	......
Phosphorus and site index	N.S.	16	N.S.	21	N.S.	21	......	......
Depth of A_1 and site index	......	......	.398*	29	......	......	......	......
Depth of $A_2 + A_3$ and site index	......	......	.441*	29	......	......	......	......
Depth of $A_1 + A_2 + A_3$ and site index	......	......	.471**	29	......	......	......	......
Depth of H layer and site index	......	......	......	......	.486*	21	......	......
Mean annual increment and site index	......	......	.644**	21	.923**	24	......	......
pH of humus and pH of C_2	......	......	.558**	21	......	......	......	......
pH of A_2 and pH C_2	......	......	.619**	21	......	......	......	......
Ratio of N in F to N in humus	......	......	......	......	.739**	21	......	......

** means that the correlation coefficient (r) is significant at the 1 percent level; * means significance at the 5 percent level; N.S. means not significant; (F) means duff layer; (H) means humus layer. Other values refer to relation of site index to tests on mineral soil.

actual examination of the soil and classification of its texture, as modified by the four important characters (tables 4 and 5) of drainage, aeration, gravel or rock content, and character of subsoil, particularly presence of material of good water-holding capacity underlying sands or loamy sands. Occasionally shallow water tables may be present within 3 to 8 feet, which will benefit site index of soils which are classed as deep sands or loamy sands, or light sandy loams. It is probable that solid bed rock within 2 feet of the surface would reduce site index by one class (10 feet) and within 1 foot by two classes (20 feet). However, no sites were examined which were in this category.

Fire history, especially indications of rather severe repeat burn, may enter into evaluation of site and growth potential of specific areas as will stocking, age of stand, and presence of hypoxylon canker or heart rot.

The correlation coefficients and the regression equations for the various relationships are given in condensed form in tables 6 and 7.

SIGNIFICANCE OF THE STUDY IN TERMS OF FOREST MANAGEMENT

The forest manager in the Lake States is faced with the problem of

Table 7. Regression equations

Figure	Equation	Correlation coefficient (r)
4	$Y = -54.57 + 1.582X$	.644**
5A	$Y = -67.18 + 1.562X$	.715**
5B	$Y = -26.24 + 0.579X$	.625**
5C	$Y = -22.86 + 0.541X$	.706**
5D	$Y = -2.41 + 0.052X$	.558**
6A	$Y = -15.82 + 0.364X$	.632**
6B	$Y = -0.29 + 0.0096X$	.537*
6C	$Y = -49.55 + 0.972X$	.595*
6D	$Y = -223.78 + 4.386X$	.498*
7A	$Y = -1.030 + .0225X$	.398*
7B	$Y = -0.536 + .0797X$	.344N.S.
7C	$Y = -3.970 + .1563X$	.441*
7D	$Y = -5.00 + .1788X$	.471**
8A	$Y = 3.45 + 0.03X$	.530*
8B	$Y = 2.73 + 0.03X$	.618**
9	$Y = 0.90 + 0.01X$	.632*
10A	$Y = 360.68 + 7.32X$	.526*
10B	$Y = -26.73 + 1.47X$	.523*
11A	$Y = 3.81 + 0.21X$	.558**
11B	$Y = 3.36 + 0.27X$	.619**
13A	$Y = 49.10 + 0.7182X - 0.0043X^2$	.704**
13B	$Y = 46.7948 + 1.2439X - 0.0109X^2$	.882**
13C	$Y = 36.8260 + 0.9337X - 0.0054X^2$	.894**
13D	$Y = 51.658 + 2.322X - 0.044X^2$	.592**
13E	$Y = 46.95 + 5.172X - 0.196X^2$	.861**
13F	$Y = 24.5774 + 8.1359X - 0.3021X^2$	.661**
14	$Y = 50.85 + 23.6826X$	.486*
15	$Y = 47.28 + 18.97X$	.545**
16	$Y = 94.61 - 17.4051X$	—.739**
17	$Y = -52.86 + 1.2803X$	.923**
18A	$Y = 49.8266 + 0.8484X - 0.0066X^2$	.677**
18B	$Y = 62.2745 + 0.5136X - 0.0055X^2$	.689*
18C	$Y = 40.9072 + 0.7591X - 0.0052X^2$	.791**

** means that the correlation coefficient (r) is significant at the 1 percent level; * means significance at the 5 percent level; N.S. means not significant.

deciding what to do with the aspen lands under his control. Aspen sites can be classified as follows:

Class	Average site index	Mean annual increment in cu. ft. per acre
1	80	62
2	70	46
3	60	32
4	50	17
5	40	5 (approx.)

The yields given are arithmetic averages of data from 48 plots in 2 states tallied in this study and refer to merchantable volume. Considering the mean annual increment, site 5 is definitely so poor that it warrants conversion to jack or red pine which will produce a mean annual increment of 20 to 25 cubic feet per acre. Site 4 is also of rather low wood production and warrants conversion to pines since these will outproduce the aspen in the ratio of at least 2 to 1 on these sites, or will produce some 35 to 40 cubic feet per acre per year for the rotation.

Site 3 aspen land has reasonably good wood production potential and it would appear to be worth while holding it until one rotation of aspen has been harvested, unless these are badly understocked or diseased. Areas of site 3 aspen have, however, already been rather extensively planted on industrial and public forests after one crop of aspen has been removed. Some warrant underplanting with spruce.

Sites 1 and 2 have a high potential for aspen production and warrant management for aspen, unless the stands are badly understocked or diseased. Many of these more productive soils are converting naturally to northern hardwoods and balsam fir (figure 21) which in most cases will make an even more valuable forest in terms of overall wood production and stumpage value.

Accepting the concept that the site 4 and 5 aspen lands, i.e., site index below 55 feet, ought to be converted, would imply that most of the aspen on the sands and poorer loamy sands ought to be converted, as well as areas of

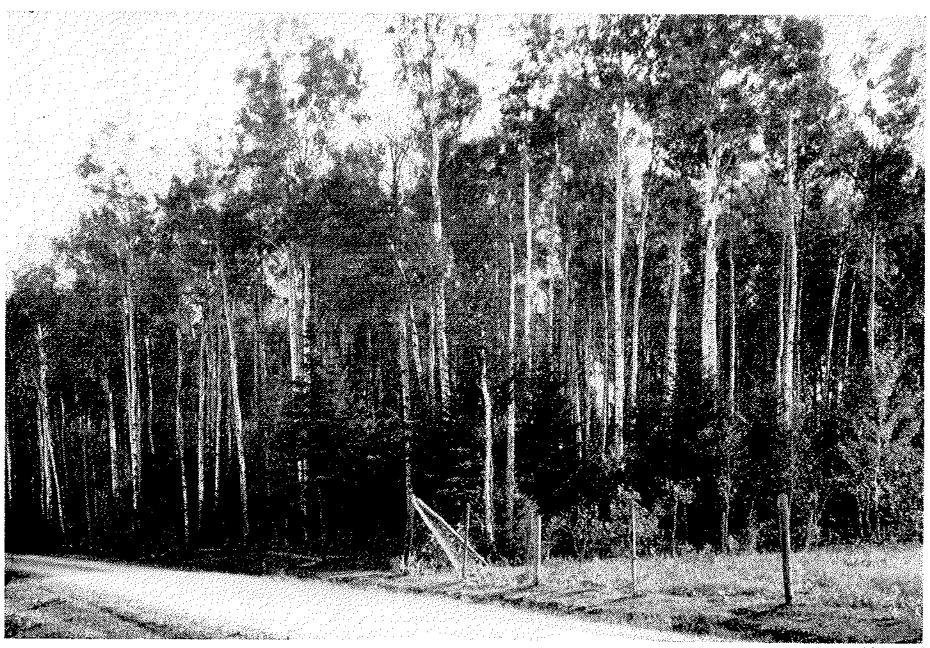

Fig. 21. A 45-year-old aspen stand in St. Louis County, Minnesota. The understory of balsam fir will furnish most of the timber volume once the aspen is cut.

repeat burn on the poorer soils. The excessively drained soils with gravelly subsoils would likewise produce more fiber if converted to jack or red pine. Borderline cases for conversion to conifers include some of the poorly drained soils with mottling within 12 inches of the surface, or heavy clays, or soils with very shallow water tables since these are often good planting sites for black or white spruce or a mixture of the two species.

Factors of growth potential, of course, are not the sole consideration in deciding whether to convert an aspen area to conifers by planting, or whether to favor other species such as balsam fir, white or black spruce, northern hardwoods, or pine which may occur in the stand. The status of stocking of the aspen and its freedom from heart rot and hypoxylon canker are also factors. The overabundance of aspen of certain age classes, i.e., 25- to 35-year age groups in many areas is a factor favoring premature cutting in this class in order to get a somewhat better distribution of age classes for the future, more particularly on larger forest properties under sustained yield management. This one age group may constitute up to 70 to 80 percent of all the aspen in some forest properties of 100,000 or more acres in size and may require breaking up if there is to be any semblance of sustained yield management.

The tables of expected site index of aspen (tables 3, 4, and 5) as related to soil texture and other modifying factors should be useful to forest managers in sizing up younger areas of aspen under 15 to 20 years old where the site index curves are not as reliable as on older stands.

One additional point of interest in the study was the marked superiority of the quaking aspen found on plots in northern Minnesota over those in northern Wisconsin, especially when interpreted as mean annual increment in cubic feet per acre (figure 22).

In stands of comparable age of 30 or more years, increment was substantially higher in the Minnesota plots. Part of the improved growth is probably due to the Minnesota soils being more favorable for aspen due to better texture, to more frequent presence of lime-rich substrates, or to soils better supplied on the average with lime, magnesium, and potash than the Wisconsin sites. The higher fertility level in the Minnesota sites apparently more than offsets the deficiency of rainfall, since the average annual precipitation in northern Wisconsin is about 30 inches. In northern Minnesota in the area where plots were taken it is only 25 inches—or a full 5 inches less than in northern Wisconsin.

For any tree species there is an epicenter or zone of optimum development where photoperiod, rainfall-evaporation ratio, temperature, elevation above sea-level, and soil nutrients are at an optimum for the growth of the species. In the Lake States, foresters generally consider northern Minnesota to be the center of optimum development for quaking aspen, followed by northern Michigan, and with northern Wisconsin and the Lower Peninsula of Michigan trailing.

In terms of latitude the zone of optimum development is at latitudes of 47° to 49° in the Lake States. In fact, it extends far northward into Canada into Ontario and westward into Manitoba, Saskatchewan, and Alberta, in an area of gray wooded and podsolic soils in a band running southeast to northwest, paralleling the prairie-forest transition for much of the distance.

Culmination of mean annual growth in the plots studied came at around 50 years in both Minnesota and Wisconsin, at which time it was about 50 cubic feet in Wisconsin and 80 in Minnesota. Assuming 90 cubic feet per cord of wood this would be equivalent to about 0.89 cords per acre per year in the Minnesota plots and about 0.55 cords per acre per year in the Wisconsin plots.

One additional point on general applicability of the data presented here on site index and soil properties that deserves mention is the fact that these probably do not apply in the prairie border areas where the scantier rainfall appears to be a critical factor. The study was not carried into these soils near the prairie, but empirical observations indicate that the aspen drops off fairly sharply in site index at the western edge of its range in northern Minnesota even on soils that have a good content of silt and clay and are adequately supplied with nutrients. It is estimated that the drop in site index in this area of northwestern Minnesota may be as much as 10 to 12 feet on soils approximating loams in texture.

The impact of decreased rainfall (and increased evaporation) in adversely affecting the growth of quaking aspen is even more sharply noticeable in the Turtle Mountain area of North Dakota (Bottineau and Rolette Counties), where the annual rainfall is about 16 inches or slightly higher. Here soils classed on some maps as gray wooded soils[3] have quaking aspen stands that are from 15 to 25 feet lower in site index than the same species on soils of comparable texture in the vicinity of Cass Lake, Minnesota, where the annual precipitation is about 22 inches. From general observation, slope, aspect, and exposure appear to be more important in areas of deficient rainfall such as the Turtle Mountains than in Minnesota. The contrast in site index in favor of north and northeast slopes over south or southwest slopes is more apparent in the Turtle Mountain area.

[3] Some of these, however, are degraded chernozems.

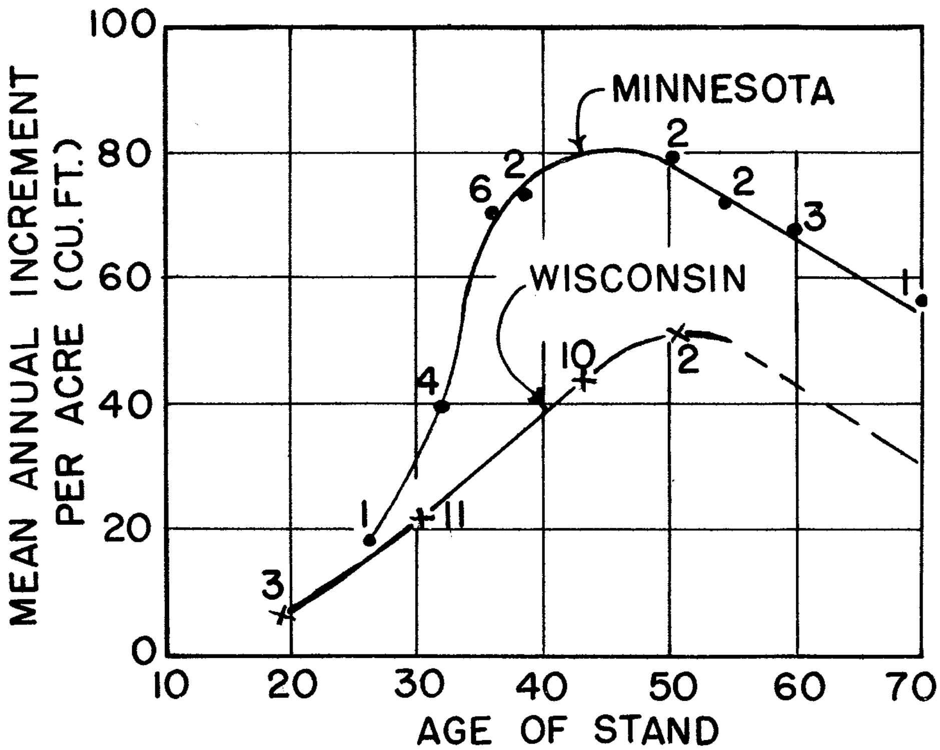

Fig. 22. Comparison of mean annual increment in cubic feet per acre in 47 aspen stands in northern Minnesota and northern Wisconsin as related to age of stand. Figures on curve represent number of plots averaged for that plot.

Summary and Conclusions

THIS STUDY involved the examination of 103 plots of quaking aspen on mineral soil and one on peat in northern Minnesota and northern Wisconsin with the objective of isolating the major soil factors that have an effect on the site index, which was used as an index of productivity. Field examination consisted of determination of site index by means of standardized age-height relationships. On 70 of the plots, soil samples were taken from pits, or from auger holes, by horizons in some plots and by fixed depths at 0-36 inches in others. These were analyzed in the laboratory. In all 104 plots, depth to the permanent water table was determined if it was within 8 feet of the surface. On 34 plots, holes were bored and texture was estimated by feel and classified as sand, loamy sand, sandy loam, etc.

The field record also included a description of soil texture, color, structure, compactness, gravel and rock content, depth to lime carbonates, depth to mottling, drainage, slope, aspect, exposure, fire history. On 45 of the plots where soil pits were dug, a record was made of depth of rooting. On these 45 plots merchantable cubic foot volume of pulpwood to 4-inch top inside bark was also determined.

Organic samples, comprising litter, duff, and humus (L, F, and H) were collected on some plots and were analyzed for chemical properties.

Soil samples taken from plots were analyzed for mechanical and chemical properties. Among the mechanical analyses were silt + clay, clay, and moisture equivalent. Other analyses included total nitrogen, available phosphorus, and replaceable potassium, calcium, and magnesium. Also determined were pH, cation-exchange capacity, and conductivity.

Relationships of soil properties to site index were determined by correlation analyses. Soils were also grouped by soil series and type, as well as by soil texture class, with a consideration of modifying factors such as shallow water tables, depth to mottling, gravel and stone content, presence of fine-textured substrates under sands or loamy sands, and fire history, especially of repeat burns in the present stand.

The major findings in the study are given below.

1. For any single criterion, the mechanical properties of the soil such as silt + clay content or moisture equivalent gave substantially higher correlation coefficients than did chemical tests for total nitrogen, or available phosphorus, or replaceable (or available) potassium, calcium or magnesium, or pH, or specific conductance. The inference is that good water relations are of vital importance to attain good growth of aspen. Optimum growth of aspen was found on loams to silt loams with about 60 percent of silt + clay content and with at least reasonably good internal drainage. Poorest growth was found on sands with less than 15 percent of silt + clay or on soils with deep, coarse, gravelly subsoils.

2. Mechanical properties and site index usually gave correlation coefficients of .592 to .894, and usually in excess of .700; these were mostly significant at the 1 percent level, and invariably significant at the 5 percent level.

3. In contrast to physical properties, chemical properties for individual nutrients were lower in the correlation coefficient which they yielded. Those that were significant were in the gen-

eral range of .430 to .632, often significant at only the 5 percent level, or in a number of cases were nonsignificant.

4. A high relationship was found between a silt + clay content of the solum (and of B_2 horizons) and nutrient level, particularly nitrogen, phosphorus, potassium, calcium, magnesium. The implication then is that finer-textured soils almost invariably have a higher nutrient level, and that the test for silt + clay content actually is a reflection not only of water-holding capacity but also of the general nutrient level. For that reason, silt + clay content gave higher correlations with site index than did the content of any single nutrient and site index.

5. The basic curve for relation of silt + clay content of the top 3 feet of soil and site index for 40 upland soils in northern Minnesota and northern Wisconsin, not affected by repeat burn, showed the following trend:

Silt + clay content	Site index
5	54
10	57
20	64
30	69
40	73
50	76
60	77
70	77
80	75
90	72

6. Shallow water tables within about 8 feet of the surface improved site index of aspen about 10 feet in case of sands, 7 feet for loamy sands, and 5 feet for light sandy loams. Shallow water tables do not benefit the finer-textured soils, and in fact tended to reduce site index slightly in loams and heavier soils. Optimum depth of water table was between 4 to 6 feet, at which depth it increased site index as much as 15 feet.

7. Plots with repeat burns due to forest fires showed a 10-foot reduction in site index over most of the range of soil texture compared with plots with no repeat burns.

8. Poor internal drainage (and poor aeration), as evidenced by strong mottling within 12 inches of the surface of soils of about 30 percent or more of silt + clay content, reduced site index of such soils by one and one-half site index classes or 15 feet.

9. Sandy soils of 5 to 20 percent silt + clay content in the surface 2 to 3 feet of soil, underlain by distinctly heavier soils of substantially higher water-holding capacity, showed a site index of about 10 to 12 feet greater than when underlain by material similar to or slightly sandier than the surface layers.

10. Coarse gravel at a depth of about 2 feet below the surface of soils rated as loams or sandy loams reduced site index of aspen by fully two site classes, or 20 feet lower than soils of that texture show normally.

11. Site index of quaking aspen was generally within a standard deviation of about ±5, if information was available on texture of surface and subsoil, gravel or clay content of subsoil, depth to water table, fire history as regards repeat burn, and depth to strong mottling.

12. For soil types represented by 5 or more plots, the standard deviation of the site index was ±4 indicating that standard detailed county soil survey maps provide a good basis for evaluating productivity of the soil for growth of aspen.

13. Substantially higher site index and greater mean annual increment was found in aspen stands in northern Minnesota than in northern Wisconsin. At culmination of mean annual growth at around age 50 these values were 80 and 50 cubic feet, respectively, for the two areas. Part of the improved growth was attributed to the more favorable status of the Minnesota soils as regards content of lime, potash, and magnesium than the Wisconsin sites sampled. The hypothesis was offered that the high content of these mineral nutrients, in the substrates of many of the Minnesota soils, especially those developed

on calcareous drifts, contributed to the longer life span of the aspen and possibly to the lower incidence of heart rot, especially after 50 years of age.

14. Depth of the combined A horizons gave a positive correlation with site index—the deeper the horizon, the higher the site index.

15. Quaking aspen is rated as a medium-rooting-depth forest species, with the depth of penetration ranging mostly from 39 to 60 inches. In all cases where calcareous substrates were present, aspen roots had penetrated into these to a distance of from 5 to 25 or more inches, in other words were tapping these C_2 layers as a source of calcium and magnesium.

16. In chemical analysis of 21 Minnesota soils from aspen of poor, fair, and good growth (for N, P, K, Ca, and Mg), a maximum contrast occurred in calcium and magnesium content of the soil with ratios of 6 to 1 and 8 to 1, respectively, for these two nutrients in the good versus poor growth regimes.

17. A composite sample from a 0- to 36-inch depth appeared to offer a simplified scheme of soil sampling, as compared with sampling individual horizons in the A + B, especially for an overall rating of average texture of the soil for the zone in which 70 to 90 percent of the root system of aspen is concentrated. However, it appears desirable to have an additional sample from a depth of 3 to 6 feet since the properties of these substrates can either add or subtract from the site potential of the upper 3 feet of soil by favorably or adversely affecting the moisture relations, and to some extent the relative abundance of bases, particularly Ca, Mg, and K.

18. Based on the equations for relationship of site index and mean annual increment in cubic feet per acre, it is concluded that the lower site index classes of aspen have such a poor potential for wood production that they should be converted to coniferous plantations.

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